



UK Climate Risk  
Independent  
Assessment (CCRA3)

# Technical Report

The [University of Exeter](#) is leading a consortium of experts who are preparing the technical chapters for the Technical Report in partnership with the [Met Office](#).

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Independent  
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# Technical Report

## Introduction

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## Key Messages and outline

This is the introduction to the Technical Report of 3<sup>rd</sup> UK Climate Change Risk Assessment (CCRA3). It sets the context for CCRA3 and provides some key background information.

- With current commitments and ambition on emissions, global warming could reach between approximately 2°C and 4°C by the end of this century, or potentially even higher.
- Even if the international community meets the goals of the Paris Agreement, further climate change will occur and hence will require adaptation.
- This CCRA3 Technical Report assesses the urgency of adapting to UK climate risks and opportunities, considering both the current climate and projected future climates consistent with two future pathways:
  - (i) stabilising 2°C by the end of the century, representing achievement of the Paris Agreement goals;
  - (ii) 4°C global warming at the end of the century the current trajectory, consistent with the current limited global ambition for reducing emissions
- This includes risks and opportunities arising from climate change within the UK and from the impacts of climate change elsewhere in the world.
- 61 risks are assessed, grouped into 5 categories:
  - Natural Environment and Assets
  - Infrastructure
  - Health, Communities and the Built Environment
  - Business and Industry
  - International Dimensions
- The extent to which current UK adaptation plans will manage these risks is also assessed, and the benefits of additional action on adaptation within the next 5 years. The risks are scored according to the urgency of additional adaptation action.

As context, section 1 gives the terms of the CCRA in the Climate Change Act (2008) and Climate Change (Scotland) Act 2009, and its purpose in informing the UK and devolved national adaptation programmes. It explains the aim of providing advice on the relative urgency of new government action on adaptation in different risk areas. The CCRA does not recommend specific actions that should be taken, as that is out of scope. Section 1 also outlines the structure of the CCRA3 process and where the Technical Report is placed within this. This section also summarises how the evidence and context has changed since the 2<sup>nd</sup> UK Climate Change Risk Assessment (CCRA2).

As background specific to CCRA3, section 2 provides the definition of risk used in this assessment. It gives a brief overview of similarities and differences in the approach of CCRA3 compared to CCRA2.

Section 2 also describes how CCRA3 frames the view of future climate change to give a clear and consistent assessment of future risks within the numerous and highly complex set of possible climate futures. This includes the consideration of potential outcomes either with or without further action on mitigation in the context of the Paris Agreement and the UK, Scottish and Welsh targets for reaching Net Zero emissions (hereafter referred to as “Net Zero”). It also introduces key aspects of the socioeconomic context, again including Net Zero, the UK’s exit from the European Union, and also the emergence of potential implications of the Covid-19 pandemic.

Section 3 outlines the sources of evidence for CCRA3, including how existing academic literature and non-academic reports are brought into the process and how these are supplemented by new analysis carried out specifically for CCRA3. The method for considering the new UK Climate Projections alongside evidence based on previous projections is introduced.

Section 4 provides an overview of the technical chapters, giving a brief summary of the scope and listing the specific risks that are examined.

## 1. Context

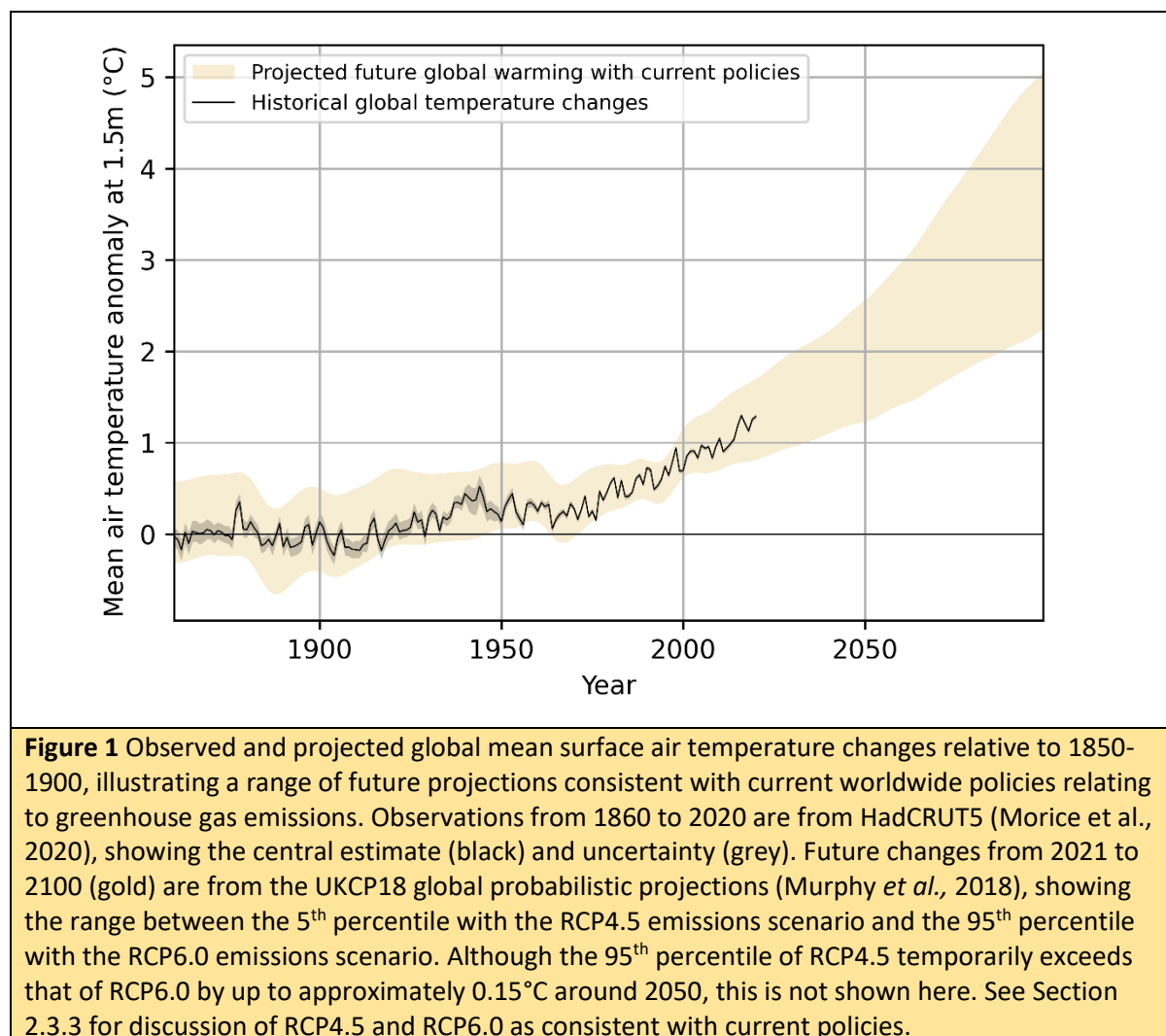
### 1.1 Human-caused climate change and the need for mitigation and adaptation

It is beyond doubt that the global climate is changing due to human alterations of the composition of the atmosphere and the character of the land surface. The global average surface temperature has risen by over 1°C compared to conditions before the industrial revolution (Chapter 1: Slingo, 2020). This is bringing unfamiliar local weather patterns, making some types of extreme weather events more likely, and causing an accelerated rise in sea levels. These changes are altering the stability of ecosystems and habitats, and increasing weather-related risks to people, both around the world and in the United Kingdom.

Although the Paris Agreement commits the nations of the world to limit global warming to well below 2°C above pre-industrial levels and pursue efforts to limit warming to 1.5°C, projections consistent with policies currently in place worldwide imply warming of between approximately 2°C and 5°C by the end of this century (Figure 1) depending on the rate of greenhouse gas emissions and the response of the climate system to these emissions. This will further increase the shifts in weather patterns and extremes, further increasing risks to people and biodiversity, with higher warming leading to greater risks.

Limiting warming to lower levels may still be achievable if global emissions are rapidly reduced to net zero or net negative, but even if global warming is successfully limited to between 1.5 and 2°C, weather patterns will still be different to those in recent decades, and sea levels will continue to rise to some extent. Adaptation to at least this minimum level of change is therefore needed, and also needs to be assessed for larger changes since the actual future level of warming and associated climate hazards cannot be known. Both mitigation and adaptation are therefore required to minimise risks from human-caused climate change.

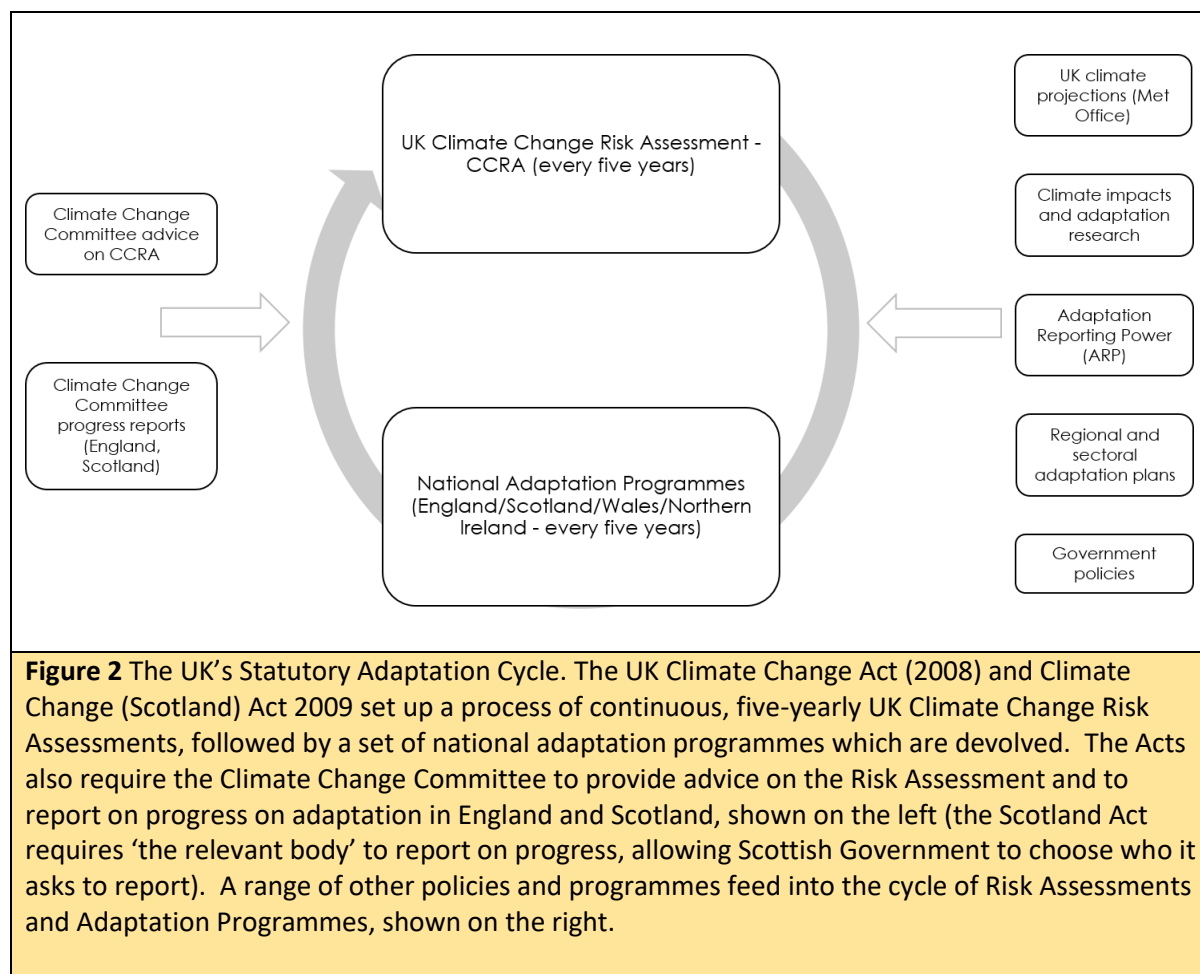




## 1.2 The Climate Change Act and National Adaptation Programme

The UK Climate Change Act (2008) and Climate Change (Scotland) Act 2009 set out a statutory five-yearly cycle of UK climate change risk assessments, followed by national adaptation programmes for England, Northern Ireland, Scotland and Wales. Each cycle leads into the next so that learning, experience and adaptation action can feed through and result in progress in adapting to climate change in the UK over time. Figure 2 shows this cycle.

The Climate Change Act also set up the Climate Change Committee and its Adaptation Committee. The Adaptation Committee has two statutory roles under the UK Act; to provide advice to the UK Government and devolved administrations on climate change risks and opportunities, and to assess progress in adapting to climate change in England. Under the Climate Change (Scotland) Act, it can also assess progress of the Scottish Climate Change Adaptation Programme. This is also shown in Figure 2.

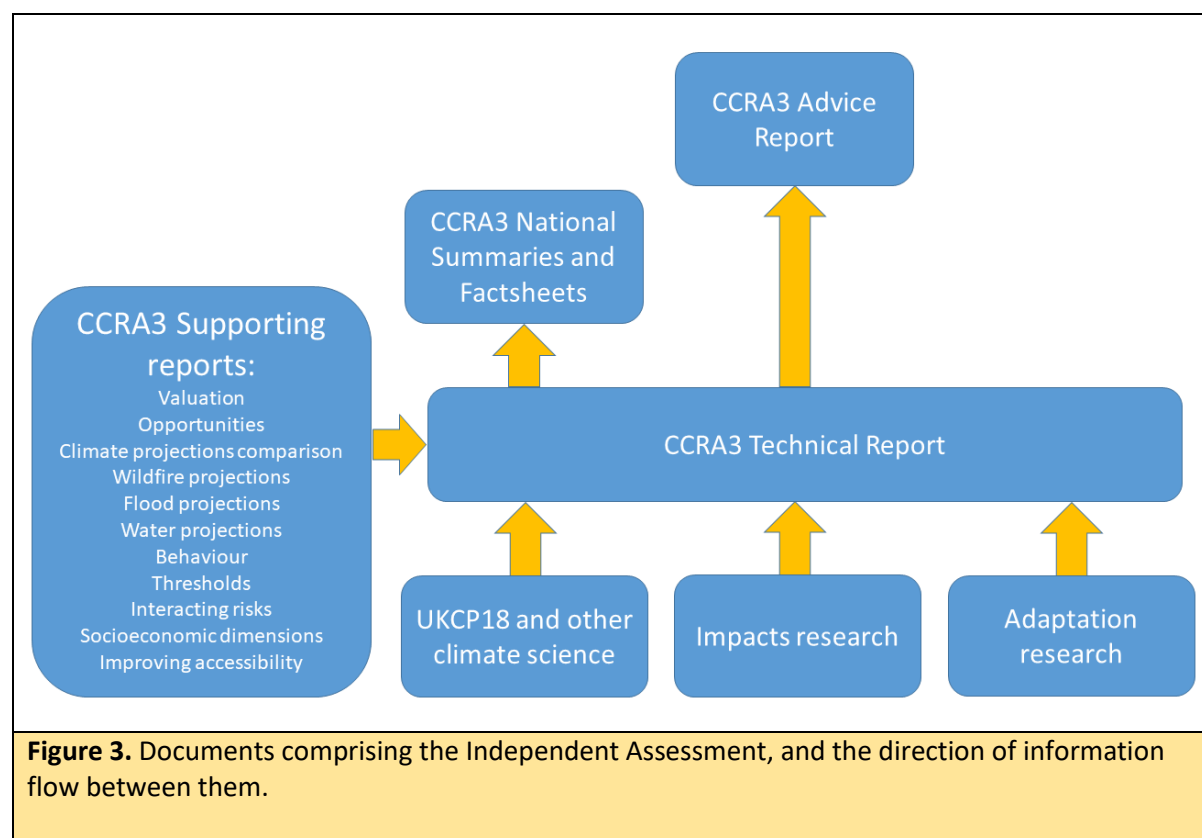


### 1.3 The Climate Change Risk Assessment (CCRA) process and structure

The first CCRA was published by the Department for Environment, Food and Rural Affairs (Defra) in 2012, and the second in 2017. For the third assessment, CCRA3, as it did for CCRA2 in 2016, Defra has asked the Adaptation Committee to prepare an Independent Assessment as a component of its statutory advice on the CCRA (see Figure 2), synthesising the latest evidence on the risks and opportunities to the UK from climate change.

This Technical Report is part of the set of reports that together make up the Independent Assessment to fulfil that request (Figure 3). It collates together the latest evidence and provides urgency scores for each risk or opportunity considered, implementing the method set out in chapter 2. In addition to the Technical Report, the Independent Assessment also consists of a number of supporting research reports, summary documents (by UK country and sector) and an Advice Report that forms the Committee's statutory advice to government. The information flow between these documents is shown in Figure 3, and the purpose of each is shown in Table 1.



**Table 1.** Purpose of documents of the CCRA3 Independent Assessment

Document	Purpose
Advice Report	Summarises and interprets the evidence provided in the technical chapters. Also provides the Adaptation Committee's statutory advice to Government on the risks and opportunities to the UK from climate change. Authored by the CCC.
Technical Report	Provides the detailed analysis that underpins the assessment of risks or opportunities, and the resulting urgency scores. Alongside this introduction, there are seven technical chapters. Evidence is drawn from the literature and new research. Authored by a consortium of experts led by the University of Exeter in partnership with the Met Office, working to the CCC.
Summaries	Two types: National Summaries that summarise the most relevant aspects of the risk assessment for each UK country (England, Northern Ireland, Scotland and Wales), and a set of seventeen factsheets that summarise the risks and opportunities for a range of topics relevant to different government bodies. Authored by a consortium of experts led by Sustainability West Midlands working to the CCC.
Supporting reports	Provides supporting evidence to inform the technical chapters, supplementing the existing literature and filling key evidence gaps from CCRA2 or updating analysis with new information. Authored by consultants working to the CCC and by researchers in other programmes.

The CCRA3 Technical Report was commissioned by the CCC but produced through a large consortium of experts coordinated by the University of Exeter in partnership with the Met Office. Authors are listed at the beginning of each Technical Report chapter.

The governance for the Independent Assessment included a Customer Group (UK Government and devolved administration funders) to provide feedback to the CCC on progress and comment on whether the outputs were fit for purpose and met the aims of the Customer Requirement, which was provided to the CCC in 2018. The Customer Group was supported by a Project Board made up of government departments and agencies from across the UK. The CCC was also supported by an expert advisory panel of independent experts who commented on the priorities and analytical approach of the assessment early on in the process.

The production of the Independent Assessment has undergone an extensive stakeholder engagement and review process. Over 450 people from 130 organisations have been involved in developing the set of reports in the assessment. The Method (Chapter 2: Watkiss and Betts, 2021) was developed by the CCC in consultation with the academic community and other stakeholders. The list of risks assessed was initially developed by the CCC and government stakeholders, and further evolved through collaboration between the Technical Report authors, the CCC and stakeholders. The CCC organised stakeholder meetings for government officials and other interested groups in London, Belfast, Edinburgh, and Cardiff throughout 2019 and into 2020. These meetings focussed on collating available evidence and policy updates. Two drafts of the technical chapters were reviewed by three different review groups; a technical peer review panel; a government review group, and a group of external reviewers who responded to an open call, in order to provide independent comments. In total, over 5,000 review comments were received on the technical chapters and the responses to each comment were collated and are available upon request. The final CCRA3 Technical Report is an independent report based on evidence from the literature and new research, having been scrutinised through the review process. Where expert interpretation has been necessary due to incomplete or conflicting evidence, this represents the views and judgement of the authors of the respective Technical Report chapters and has been identified as such.

The primary intended audience for the Independent Assessment is the departments of the UK Government, departments of the devolved administrations, and their respective Arm's Length Bodies. The Government also asked that the report is written with a secondary audience in mind of organisations making significant policy or investment decisions. These key stakeholders have been involved throughout the process, in particular through the scoping the CCRA3 Technical Report and providing input relating to adaptation issues within their remit. It should be noted however that the individual chapters of the CCRA3 Technical Report are the product of their respective authors only (listed at the front of each chapter). The accompanying Advice Report represents the Climate Change Committee's interpretation of the evidence set out in the Technical Report, including their official advice as required under the UK Climate Change Act (2008).

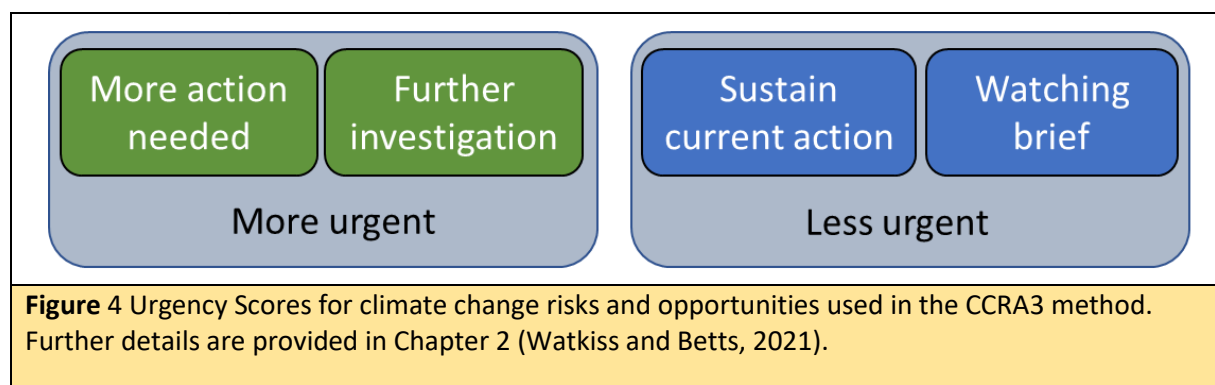
### 1.4 Purpose of the CCRA

The aim of the CCRA3 Independent Assessment is to address the following question, as it was for the previous CCRA:



*“Based on our latest understanding of current, and future, climate risks/opportunities, vulnerability and adaptation, what should the priorities be for the next UK National Adaptation Programme and adaptation programmes of the devolved administrations?”*

As for CCRA2, the analysis set out in this report seeks to characterise each risk or opportunity by scoring the degree of urgency it poses in the next five years – more urgent risks and opportunities being classified as either ‘more action needed’ or ‘further investigation’ (Figure 4). For the former, the Urgency Score implies that additional adaptation is needed urgently, either over and above what is already happening, or in some cases adaptation needs to start in cases where there is currently nothing happening. Further investigation denotes risks or opportunities where not enough evidence is available to make a robust judgement on what further action is needed. Less urgent risks and opportunities are not scored as ‘do nothing’ but rather as either sustaining current action if the amount of action is in line with the magnitude of the risk or opportunity, or as a ‘watching brief’ where further action is not currently justified, but monitoring the situation is.



It is important to note that this report focusses on current and future risks and not the specific adaptation actions that are needed to reduce risk in the future. The report identifies specific areas where further action is felt to be needed, based on the available evidence. It does not take the further step of recommending what specific actions should be taken, though it does discuss the benefits of taking further action, and this by necessity includes commentary on specific actions. The task for the UK Government and devolved administrations, following this assessment, is weighing up the costs and benefits of different options and setting objectives and actions in the next national adaptation programmes.

This CCRA3 Technical Report draws on the new adaptation policies and programmes set out in updated national adaptation programmes published since CCRA2 (Defra (2018), Welsh Government (2019), Scottish Government (2019), Department of Agriculture, Environment and Rural Affairs (Northern Ireland (2019)).

## 1.5 Evolution of the evidence and context since the 2<sup>nd</sup> UK Climate Change Risk Assessment

Scientific evidence for ongoing climate change and the role of human influence has continued to accumulate and further strengthen since CCRA2. This is partly because climate change itself is continuing, and partly because observational datasets and techniques for analysis and modelling continue to improve. Methods for quantifying the influence of climate change on the likelihood and severity of extreme weather events have been developed further and applied more widely (Swain *et al.*, 2020; Herring *et al.*, 2021). The assessment of the potential for unprecedented events even under the current climate is a particular area of substantial progress since CCRA2 (e.g., Thompson *et al.*, 2017). Furthermore, the new generation of climate models, with updated representations of scientific understanding and higher spatial and temporal resolution, has improved skill in simulating some regional climate processes, and these form a key part of the new UK Climate Projections (Lowe *et al.*, 2018). Analysis and understanding of socioeconomic components of climate risk has also evolved, and more integrated approaches to risk assessment are becoming more widely employed. A number of national climate risk assessments have been published in various countries, as described in Chapter 2 (Watkiss and Betts, 2021), with new approaches to the communication of climate risk being developed and implemented (Sustainability West Midlands, 2020).

The political and societal context has also evolved significantly since CCRA2 was published in 2017. Following the publication of the IPCC Special Report on Global Warming at 1.5°C (IPCC, 2018), numerous countries are preparing more ambitious climate mitigation commitments than previously adopted following the publication of the IPCC Special Report on Global Warming at 1.5°C. This includes the UK's ambition and statutory target to achieve Net Zero greenhouse gas emissions by 2050, with separate accompanying targets for Net Zero by 2045 in Scotland, 2050 in Wales, and a target still to be confirmed for Northern Ireland. Worldwide this is a rapidly-changing situation, with new announcements of country targets being made in advance of COP26. Alongside this, public concern over climate change has become much more prominent, with growing calls for stronger action accompanied by campaigns taking various forms including pressure group activity, school strikes and civil disobedience. Citizens Assembly approaches are being implemented as a means of facilitating and publicising structured public discussion on climate change, with the Climate Assembly UK being one example (Climate Assembly UK, 2020).

Other potentially important changes in the socioeconomic context include the UK's exit from the European Union, and the shifts this will create in environmental policy, trade, and potentially, cooperation on issues such as monitoring and shared research programmes.

Moreover, and significantly, the world has been dealing with the effects of the SARS-Cov-2 (Covid) pandemic, which at the time of writing remains severe and ongoing. The long-term effects of the pandemic are difficult to predict, and there are potentially profound effects on human vulnerability to climate change through increasing inequality, reduced resources and capacity to cope with other shocks. The experience of the pandemic could also lead to a change in how governments view and plan for risk, but it remains too early to tell at the time of writing.

## 2. The CCRA3 approach to assessing climate change risks and opportunities for the UK

### 2.1 Definition of risk and opportunity

This Report uses the same definition of risk as was presented in the CCRA2 Evidence Report; ‘the potential for consequences where something of value is at stake and where the outcome is uncertain’. When used in its general sense, the word ‘risk’ is taken to include both negative and positive consequences, and so includes opportunities. However, the CCRA3 method differentiates between *assessing* negative risks and positive opportunities, and these are reported separately throughout the technical chapters and in the synthesis report as far as possible. The risk descriptors (see Section 4 below) are marked up as risks, opportunities, or both in some cases where there are a range of effects on a given receptor.

Risk assessments often use measures of probability and consequence to characterise the risk, and attempts are made to define these quantities as accurately as possible. Some risk assessments consider the potential for a specific event to happen, as is done in the UK National Risk Assessment which is led by the Cabinet Office. Other studies, particularly climate change risk assessments often look at the potential change (e.g., mean or variability) in a variable such as temperature or rainfall.

In all cases, climate change risk assessments must cope with a large amount of uncertainty. Although all of the risks discussed in this report have some implicit likelihood associated with them, it cannot be quantified precisely. In some cases, we have collected information on probabilities attributed to changes in variables or events, based on an understanding of how the physics of the climate system may change in the future. Climate simulations such as those presented in the 2018 UK Climate Projections (UKCP18: Lowe *et al.*, 2018) and other sets of projections give a current best estimate of which changes in the UK and global climate are more or less likely than others for any given emissions scenario, but these probabilities do not include all sources of uncertainty, and only represent changes in the climate such as temperature and sea level, rather than impacts such as flooding. Rather than provide an estimate of likelihood for individual risks, the authors estimate the magnitude of the impact specified in the name of the risk descriptor, for specific time periods in specific climate futures - the 2050s and 2080s on pathways to approximately 4°C and 2°C global warming in the late 21<sup>st</sup> Century. These are considered to broadly represent lower and upper rates of climate change consistent with either current policies relating to greenhouse gas emissions or the successful achievement of international climate policy ambitions - the rationale for each is described in Section 2.3 below. The definition of magnitude is outlined in Chapter 2 (Watkiss and Betts, 2021).

As well as estimating the magnitude of specific impacts within the range of 2°C to 4°C global warming late this century, the assessment also considers low likelihood, high impact events that sit outside of the assessment of magnitude. The approach to this is described below and set out in more detail in Chapter 2.

As a risk assessment, the focus of CCRA3 is not necessarily on the most likely outcomes, but on outcomes that are likely enough to warrant consideration. The judgement of this depends on the

magnitude of the potential impact – an event which would have extremely severe consequences may warrant consideration in the risk assessment even if it has a very low likelihood of occurring.

## 2.2 Risks and opportunities considered in CCRA3

CCRA3 assesses a set of 61 specific risks and opportunities to the UK from climate change (Table 2). As was the case for CCRA2, the list of risks and opportunities (Table 2) was decided on through an extensive process of consultation between the Government Customer, the CCC and the authors of the technical chapters. Taking the list from CCRA2 as a starting point, the CCRA Customer Group and Project Board suggested various modifications to make the list more policy relevant. The list was refined over a 9 month period with input from the CCC's Adaptation Committee and the chapter authors, and was refined further after the first order draft chapters were produced to limit duplication of analysis across different risks and to fill a few gaps identified by the authors. The focus of the list is to create a set of risks and opportunities that have direct relevance to different government bodies.

**Table 2** Risks and opportunities assessed in the CCRA3 Technical Report

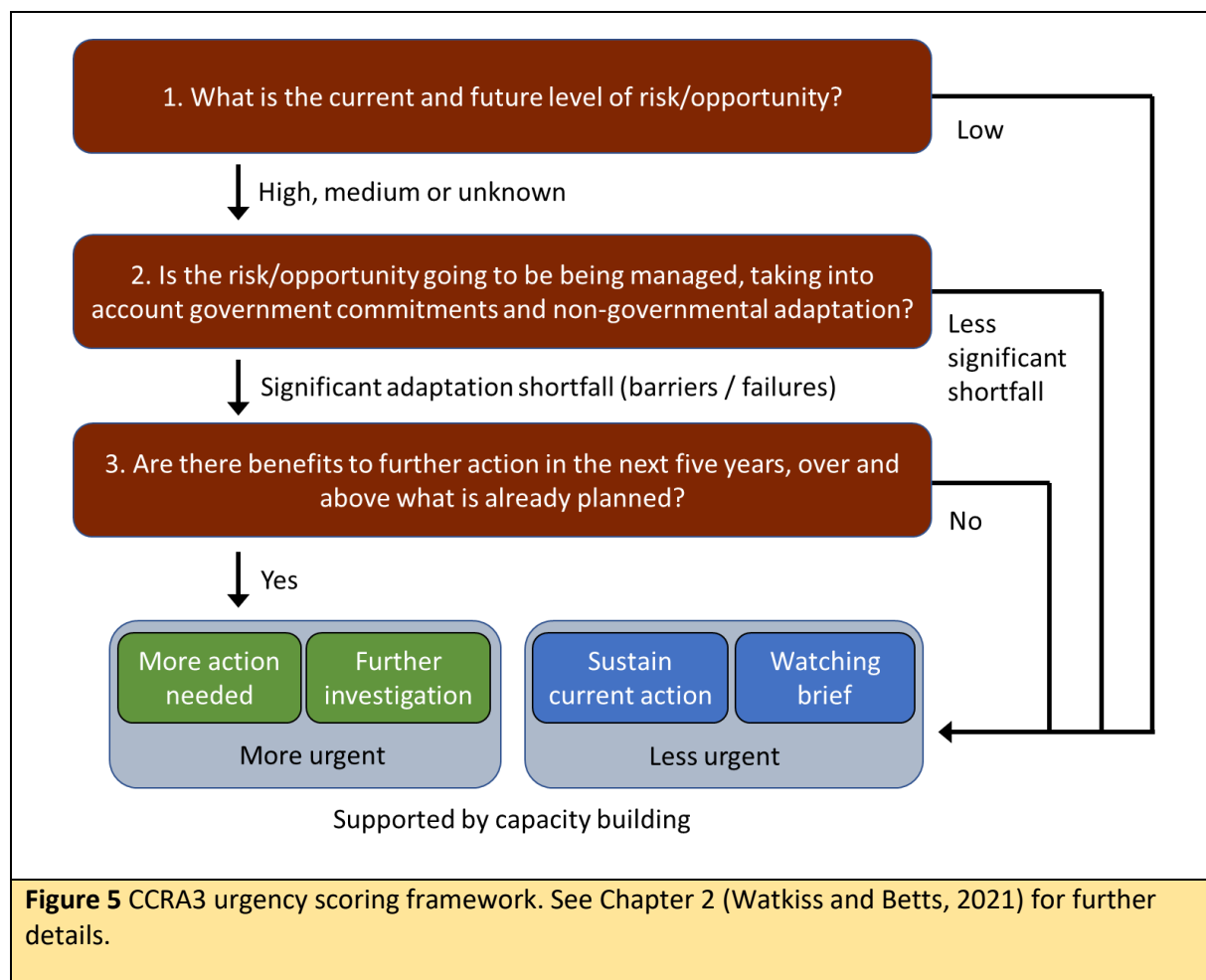
	<b>Natural Environment and Assets</b>
N1	Risks to terrestrial species and habitats from changing climatic conditions and extreme events, including temperature change, water scarcity, wildfire, flooding, wind, and altered hydrology (including water scarcity, flooding and saline intrusion).
N2	Risks to terrestrial species and habitats from pests, pathogens and invasive species
N3	Opportunities from new species colonisations in terrestrial habitats
N4	Risk to soils from changing climatic conditions, including seasonal aridity and wetness.
N5	Risks and opportunities for natural carbon stores, carbon sequestration from changing climatic conditions, including temperature change and water scarcity
N6	Risks to and opportunities for agricultural and forestry productivity from extreme events and changing climatic conditions (including temperature change, water scarcity, wildfire, flooding, coastal erosion, wind and saline intrusion).
N7	Risks to agriculture from pests, pathogens and invasive species
N8	Risks to forestry from pests, pathogens and invasive species
N9	Opportunities for agricultural and forestry productivity from new/alternative species becoming suitable.
N10	Risks to aquifers and agricultural land from sea level rise, saltwater intrusion
N11	Risks to freshwater species and habitats from changing climatic conditions and extreme events, including higher water temperatures, flooding, water scarcity and phenological shifts.
N12	Risks to freshwater species and habitats from pests, pathogens and invasive species
N13	Opportunities to freshwater species and habitats from new species colonisations
N14	Risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures.
N15	Opportunities to marine species, habitats and fisheries from changing climatic conditions
N16	Risks to marine species and habitats from pests, pathogens and invasive species
N17	Risks and opportunities to coastal species and habitats due to coastal flooding, erosion and climate factors.
N18	Risks and opportunities from climate change to landscape character
	<b>Infrastructure</b>
I1	Risks to infrastructure networks (water, energy, transport, ICT) from cascading failures



I2	Risks to infrastructure services from river, surface water and groundwater flooding
I3	Risks to infrastructure services from coastal flooding and erosion
I4	Risks to bridges and pipelines from flooding and erosion
I5	Risks to transport networks from slope and embankment failure
I6	Risks to hydroelectric generation from low or high river flows
I7	Risks to subterranean and surface infrastructure from subsidence
I8	Risks to public water supplies from reduced water availability
I9	Risks to energy generation from reduced water availability
I10	Risks to energy from high and low temperatures, high winds, lightning
I11	Risks to offshore infrastructure from storms and high waves
I12	Risks to transport from high and low temperatures, high winds, lightning
I13	Risks to digital from high and low temperatures, high winds, lightning
<b>Health, Communities and the Built Environment</b>	
H1	Risks to health and wellbeing from high temperatures
H2	Opportunities for health and wellbeing from higher temperatures
H3	Risks to people, communities and buildings from flooding
H4	Risks to the viability of coastal communities from sea level rise
H5	Risks to building fabric
H6	Risks and opportunities from summer and winter household energy demand
H7	Risks to health and wellbeing from changes in air quality
H8	Risks to health from vector-borne disease
H9	Risks to food safety and food security
H10	Risks to water quality and household water supplies
H11	Risks to cultural heritage
H12	Risks to health and social care delivery
H13	Risks to education and prison services
<b>Business and industry</b>	
B1	Risks to businesses from flooding
B2	Risks to businesses and infrastructure from coastal change from erosion, flooding and extreme weather events
B3	Risks to business from water scarcity
B4	Risks to finance, investment and insurance including access to capital for businesses
B5	Risks to business from reduced employee productivity due to infrastructure disruption and higher temperatures in working environments
B6	Risks to business from disruption to supply chains and distribution networks
B7	Opportunities for business from changes in demand for goods and services
<b>International Dimensions</b>	
ID1	Risks to UK food availability, safety, and quality from climate change overseas
ID2	Opportunities for UK food availability and exports from climate impacts overseas
ID3	Risks and opportunities to the UK from climate-related international human mobility
ID4	Risks to the UK from international violent conflict resulting from climate change overseas
ID5	Risks to international law and governance from climate change that will impact the UK
ID6	Opportunities from climate change (including Arctic ice melt) on international trade routes
ID7	Risks associated with international trade routes
ID8	Risk to the UK finance sector from climate change overseas
ID9	Risk to UK public health from climate change overseas
ID10	Systemic risk arising from the amplification of named risks cascading across sectors and borders

## 2.3 CCRA3 Urgency Scoring approach compared to CCRA2

The CCRA3 Technical Report assesses the urgency of adaptation to the risks and opportunities in Table 2 with a 3-step Urgency Scoring approach (Figure 5). This follows a broadly similar approach to CCRA2.



Step 1 assesses the current and future magnitude of risk, and step 2 assesses the extent to which the risk will be addressed by current adaptation or adaptation already planned. Step 3 assesses the benefits of additional action within the next 5 years. The approach has been further developed to bring in further information within these steps, such as the potential for lock-in of inappropriate or maladaptive responses, the potential to exceed critical thresholds that impact on the effectiveness of adaptation, and interactions between individual risks. For each risk, these 3 main steps and additional sub-steps determine the urgency score (Figure 5).

For risks and opportunities within the UK, the risk magnitude and adequacy of current adaptation were assessed for each of the 4 UK nations wherever possible. Where there was not sufficient evidence to distinguish between the nations, the same risk magnitude and adaptation scores were assigned to all. The overall urgency score was provided for all nations. International risks and opportunities were assessed at the level of the UK as a whole.

As with CCRA2, much of the evidence for the risk assessment is drawn from the existing literature. However, more substantive bespoke research has been possible in CCRA3 compared to CCRA2, enabling some key knowledge gaps to be addressed, including socioeconomic scenarios, interacting risks, thresholds in the natural environment, and human behaviour (see Chapter 2, Watkiss and Betts 2021, section 2.2.4).

A further difference in approach is necessitated by the publication of new climate projections, UKCP18. Although the assessment of several risks benefitted from new analysis using UKCP18, much of the existing evidence on future UK risks is based on earlier projections such as UKCP09, so the approach needed to take account of this. This is described further in Section 3.3 below, and in Chapter 2.

## 2.4 Framing the current and future climate context for CCRA3

### 2.4.1 Overview

Assessing the urgency of adaptation requires information on climate and weather conditions that could occur under current and future conditions.

Assessment of the current risk magnitude take account of current weather and climate hazards and the exposure and vulnerability of people and the natural environment to these hazards. The overall risk may already have been present in a climate unperturbed by human influence, or may have increased in recent years due to changes in climate, socioeconomic factors, or non-climatic human influence on the environment (such as land use affecting habitats).

For the current climate, observed weather data clearly provides a major source of evidence for trends in average climate conditions, the magnitude of extreme weather conditions that can already occur, and whether these extremes are changing. Observed trends in data relating to ecosystems or people potentially provide evidence for whether impacts are occurring, and impacts of past extreme weather events also provide data on the magnitude of current risks. Event attribution techniques can be used to assess the change in likelihood of extreme weather events, not only for changes in temperature extremes but also now for extreme precipitation (Swain *et al.*, 2020; Herring *et al.*, 2021).

However, observed data may not capture the full range of possibilities or give a true picture of the likelihood of particular events, even under the current climate. By definition, extreme events are rare and hence may not have yet occurred in particular locations, even if they are possible. Similarly, some events may have occurred occasionally, but are actually more likely than would be expected from past statistics. Recent advances in climate science have made it possible to assess the likelihood of rare or unprecedented events (Chapter 1: Slingo, 2021). This new capability, along with analysis of observed trends and event attribution, can in principle be used to inform an assessment of the current magnitude of risks, which may now be higher than that assumed purely on the basis of past experience.

For future climate, a very wide range of conditions are possible, depending on natural climate variability, the extent of human influence, and the response of the climate system to this influence. Future climate projections are often framed in terms of climate system responses to specific

scenarios of emissions or specific rates of build-up greenhouse gases in the atmosphere. However, CCRA3 takes a different approach. Since the focus of the CCRA is on informing adaptation, the assessment is framed in terms of risks associated with particular future pathways of future climate change which could come about through different combinations of circumstances, rather than focussing on the details of how these pathways may come about.

Specifically, the framing for future climate this century is in terms of two main outcomes for detailed analysis, plus a third set of outcomes providing wider context for the risk assessment:

- (i) An approximate minimum level of global warming that can be expected if humans take action to reduce their influence on climate. This provides information on the minimum level of change for which further adaptation will be necessary.
- (ii) An approximate maximum rate of global warming consistent with a continuation of current human influence, accounting for uncertainties in anthropogenic greenhouse gas emissions and the climate system response. This quantifies the risks that we wish to avoid or reduce through mitigation, or for which adaptation may be needed if no mitigation action occurs. A maximum rate of warming is considered, rather than a central estimate, since this is a risk assessment rather than a prediction of “most likely” futures
- (iii) Higher rates of warming above those currently considered consistent with the current trajectory, and low-likelihood, high-impact events such as climate system tipping points. Again, this is necessary in a risk assessment since the future cannot be predicted with high confidence.

The first outcome is represented by a pathway in which warming is limited to approximately 1.5°C to 2.5°C global warming, and the second by a pathway in which warming reaches approximately 4°C global warming between 2080 and 2100 (Figure 6). Both of these are used for detailed analysis in the assessment, and the rationale for each is described below. The use of approximate rather than precise definitions of global warming levels allows a number of relevant projections to be included in the evidence base for each, including the 5<sup>th</sup> Coupled Model Intercomparison Project (CMIP5) models and the previous set of UK projections, UKCP09, amongst others, some using RCP scenarios and others using different scenarios<sup>1</sup>. Further details of the sets of projections and scenarios aligned to both the 2°C and 4°C warming pathways are provided in Chapter 2 (Watkiss and Betts, 2021).

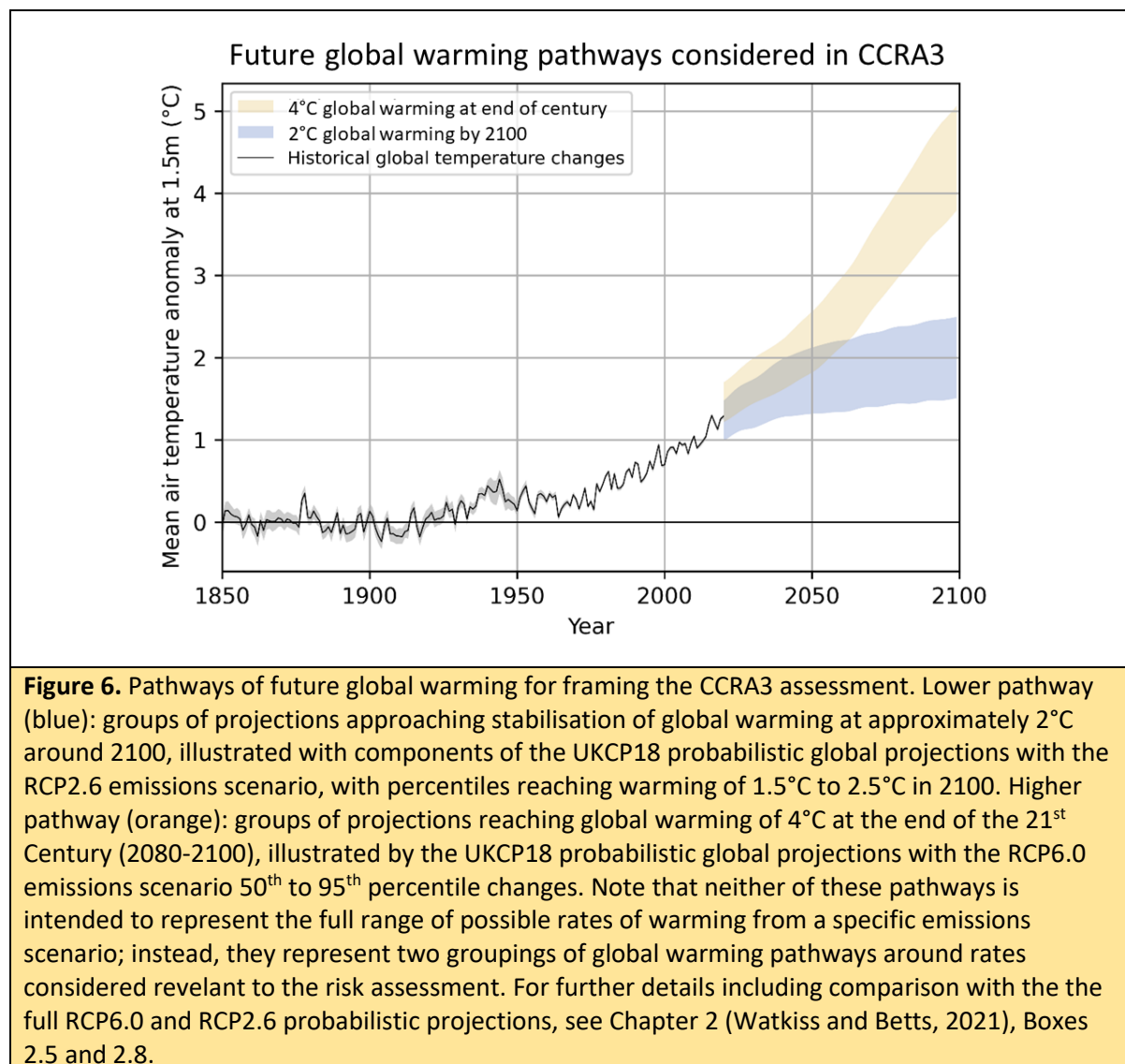
The third group of outcomes recognises the possibility of even higher rates of warming, as part of a wider approach of considering low-likelihood, high-impact outcomes to allow for informed decision-making in cases when such outcomes may be important. Such a very high scenario is distinct from the scenario of approximately 4°C global warming at the end of century. The rationale for the distinction between these scenarios and the upper bound of the higher ‘main analysis’ scenario is provided below.

Information on low-likelihood, high-impact events is also considered. Some of these, such as tipping points or strong feedbacks involving the carbon cycle, may themselves lead to faster rates of warming or sea level rise. Others may change the climate outcome to one of an entirely different

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<sup>1</sup> The new CMIP6 climate models are driven by the Shared Socioeconomic Pathway (SSP) scenarios rather than the RCPs. However, since the CCRA3 assessment is framed in terms of pathways to global warming levels rather than emissions scenarios, the use of the RCPs does not affect the relevance or timeliness of the analysis.

nature to that in the main projections. These are not used directly for assessing the magnitude of risks or for scoring the urgency of adaptation, but are presented as wider context so that they can be considered if any adaptation decisions are very sensitive to low-likelihood, high-impact outcomes.



#### 2.4.2 Lower pathway: approximately 2°C global warming in the late 21<sup>st</sup> Century

The lower scenario represents an approximate minimum level of future climate change to which adaptation will be necessary, defined as a stabilisation of global warming at 2°C above 1850-1900 levels by 2100 with a tolerance of  $\pm 0.5^\circ\text{C}$  (Figure 6). This therefore includes outcomes which meet the aims of the Paris Agreement by limiting warming to between 1.5°C and 2°C, and also allows for consideration of studies with “temperature overshoot” scenarios reaching up to 2.5°C warming. This range encompasses a large proportion of the UKCP18 global probabilistic projections with the RCP2.6 emissions scenario and CMIP5 projections with the RCP2.6 concentration pathway.<sup>2</sup>

<sup>2</sup> The RCPs (Representative Concentration Pathways) are used in two ways: (i) emissions scenarios, when Earth System Models calculate the change in CO<sub>2</sub> concentrations, accounting for climate-carbon cycle feedbacks, as

This broad definition with a tolerance of  $\pm 0.5^{\circ}\text{C}$  should not be taken to imply that the difference between  $1.5^{\circ}\text{C}$  and  $2^{\circ}\text{C}$  global warming is considered negligible. The IPCC (2018) clearly demonstrated that at the global scale, projected global impacts are generally larger at  $2^{\circ}\text{C}$  warming compared to  $1.5^{\circ}\text{C}$ . It is simply that a greater level of precision is not justified in the context of the 4 broad categories of urgency score used to frame the outputs of the CCRA3 Technical Report (Figure 4). Since climate change uncertainties are more substantial at smaller scales (see Chapter 1: Slingo, 2021), many of the possible UK-scale risks associated with over  $2^{\circ}\text{C}$  global warming could also apply at  $1.5^{\circ}\text{C}$  warming. Hence, a wide definition of the scenario ensures that all studies with relevant information for a minimum level of UK climate risk can be considered.

#### 2.4.3 Higher scenario: approximately $4^{\circ}\text{C}$ global warming at the end of the 21<sup>st</sup> Century

The higher scenario represents a rate of global warming that could occur if action to mitigate climate change fails to go beyond current pledges. This is not necessarily the most likely rate of warming – rather, it is a level of warming considered sufficiently likely to warrant consideration in the context of a risk assessment. This likelihood is judged on the basis of two factors:

- i) Future global emissions in the absence of stronger action on climate change mitigation.
- ii) The response of the climate system to those future emissions.

Both of these contributions to future warming are subject to substantial uncertainties.

Quantifying future emissions in the absence of stronger climate mitigation action is challenging and subject to high uncertainty, and is also subject to ongoing change in context. Although estimates of such emissions are routinely made (United Nations Environment Programme, 2020; Climate Action Tracker, 2021), these are intended to provide a systematic means of comparing the implications of new international commitments as a tool for monitoring progress on mitigation policy rather than providing information for risk assessments<sup>3</sup>. For a risk assessment such as CCRA3, a more comprehensive assessment of the range of potential outcomes is required.

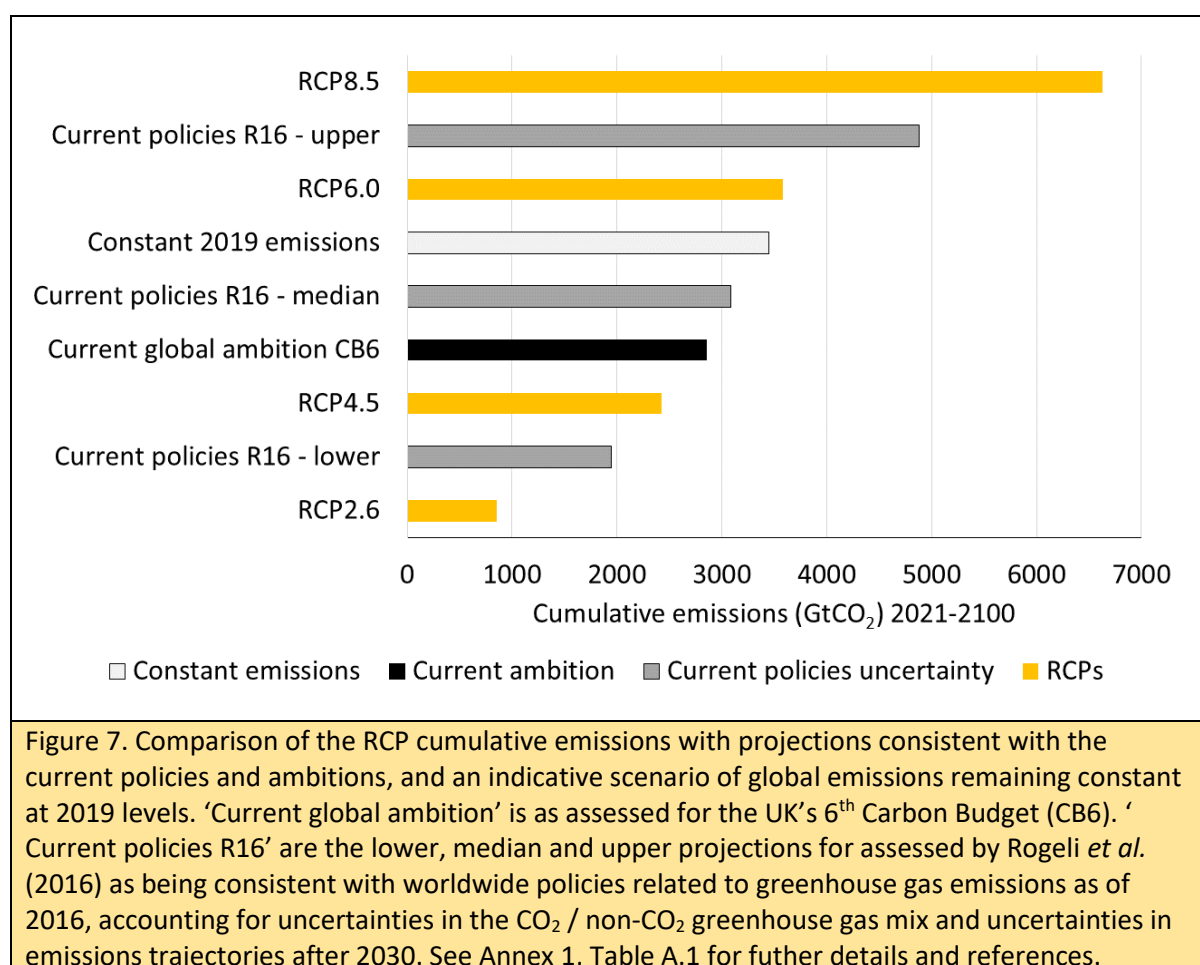
Predictions of political, economic, technological and societal futures are inherently deeply uncertain, and risk assessments need to consider the implications of this uncertainty. Moreover, with new national commitments on emissions being announced regularly, central estimates of future emissions trajectories require regular updates.

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in UKCP18, and (ii) concentration pathways, as input to atmosphere-ocean models which do not make carbon cycle calculations, as in the CMIP5 models. This distinction is important as it can affect the projected rates of  $\text{CO}_2$  rise (Booth et al., 2017) and consequent rate of global warming (Hausfather and Betts, 2020). The same names are commonly applied to both uses. To distinguish between these two uses, the CCRA3 Technical Report adds “emissions scenario” and “concentrations pathway” after the RCP name.

<sup>3</sup> For example, the Climate Action Tracker (2021) uses a simple climate model and presents uncertainties in future global warming between the 16th and 84th percentiles of the probability distribution. CCRA3 uses the UK Climate Projections which are based on a number of climate models constrained against observed climate change, and considers the 5<sup>th</sup> to 95<sup>th</sup> percentile uncertainty range.

If emissions remain at current levels<sup>4</sup> from 2021 until 2100, cumulative CO<sub>2</sub> emissions would be approximately 3400 Gigatonnes (GtCO<sub>2</sub>). If pre-2020 Nationally Determined Contributions (NDC) commitments are implemented by 2030 and then decarbonisation continues at the same rate, cumulative emissions would reduce to approximately 2900 Gigatonnes (Vivid Economics and UCL, 2020). However, while the near-term trajectory of global fossil fuel emissions can be projected with some degree of confidence, uncertainties are much higher for emissions trajectories beyond the next one to two decades (Rogeli *et al.*, 2016). Considering currently implemented policies in 2016 (as opposed to NDCs, which are merely commitments), cumulative emissions from 2021 to 2100 range from approximately 2000 to 4900 GtCO<sub>2</sub>, with a median of approximately 3100 (Figure 7: Rogeli *et al.*, 2016)<sup>5</sup>. Therefore, rather than basing the risk assessment on a single best estimate of future emissions, a range of potential emissions needs to be considered.



The UKCP18 climate projections are driven by emissions scenarios associated with the Representative Concentration Pathways (RCPs). Of these, the cumulative emissions associated with RCP4.5 and RCP6.0 are within the range consistent with current policies (Figure 7). The RCP8.5 emissions scenario is above the upper end of the current policies range (Hausfather and Peters, 2020) and RCP2.6 is below the lower end.

<sup>4</sup>Total anthropogenic emissions of 43 GtCO<sub>2</sub> per year in 2019, including fossil fuel use, land use change and cement production. While emissions were lower in 2020, they have returned to approximately 2019 levels in early 2021.

<sup>5</sup> Projected cumulative emissions for 2011-2100 (Rogeli *et al.*, 2016), minus historical cumulative emissions 2012-2020 (Friedlingstein *et al.*, 2020)



For a risk assessment, it is not necessary to capture the full range of possibilities consistent with current trajectories: the focus is naturally on the higher end of the full set of possibilities. To provide such a focus while allowing a usefully large set of relevant literature to be considered, the CCRA3 higher warming pathway is defined as the range between the 50<sup>th</sup> and 95<sup>th</sup> percentiles in the UKCP18 projections driven by RCP6.0 emissions. The 50<sup>th</sup> percentile of the global annual temperature anomaly exceeds 3.5°C global warming by 2100 of the century, and the 95<sup>th</sup> percentile reaches 4°C global warming in 2080 and nearly 5°C in 2100 (Figure 6). Emissions trajectories in the upper part of the range consistent with current policies therefore bring a substantial likelihood of global warming exceeding 4°C within this century – nevertheless, it is not the most likely outcome, especially since emissions lower than RCP6.0 are also consistent with current policies. The 50<sup>th</sup> to 95<sup>th</sup> percentile range with RCP6.0 emissions includes projections used in a wide pool of literature with impacts projections applicable to a scenario of approximately 4°C warming in the late century, including studies that used previous generations of scenarios such as those from the IPCC Special Report on Emissions Scenarios (SRES: Nakićenović, *et al.*, 2000).

It is important to note that many impacts will continue to increase in magnitude after 2100, especially if warming is still ongoing at that time. Even if warming is limited to approximately 2°C, sea level rise is projected to continue due to ongoing melting of land ice and thermal expansion of ocean waters – with an extended RCP2.6 scenario, global sea level rise could reach over to 2m by 2300 (Palmer *et al.*, 2018). Higher emissions scenarios are projected to lead to larger rises. The implications of these longer-term risks are not explored in CCRA3 because the aim is to assess the urgency of adaptation, but they provide additional context on the benefits of mitigation.

The timing of reaching a particular climate state is a crucial element for informing adaptation. The CCRA3 Technical Report assesses risks in the 2050s and 2080s on pathways to levels of global warming of 2°C and 4°C at the end of the century.

The above pathways to 2°C and 4°C global warming are broadly representative of climate futures with and without further international action on mitigation, so comparison of the assessed magnitudes of the risks on each of these pathways could be considered to be approximately indicative of the reduction in UK climate risks by meeting the Paris Agreement objectives as imprecisely defined above. However, it is emphasised that this is not the primary purpose of the CCRA3 method and should not be interpreted as a rigorous assessment of the benefits of mitigation.

#### 2.4.4 Higher rates of global warming as part of the Low Likelihood High Impact assessment

In order to provide the widest possible context for assessment of adaptation urgency, the CCRA3 Technical Report also includes a general, less detailed consideration of low likelihood, high-impact outcomes, including rates of global warming faster than that reaching 4°C in 2080. Such rapid warming could arise if emissions grew along a pathway higher than those consistent with current policies, or from emissions consistent with current policies if feedbacks in the climate system are stronger than in the projections used here. The latter may require the passing of one or more tipping points in the climate system, most of which are considered to be of low likelihood but highly

consequential if they were to be passed. Chapter 1 (Slingo, 2021) describes some of these tipping points and their potential implications for climate change in the UK.

The above categories of Low Likelihood High Impact (LLHI) scenarios are not examined in detail for each risk but are addressed in a general way in each chapter. Chapter 2 provides further details, including definitions of which climate projections are included in the main analysis and which are LLHI high warming scenarios.

## 2.5 Current and future socioeconomic context for CCRA3

With risk consisting of hazard, vulnerability and exposure, the latter two components depend on socioeconomic factors and can also be modified by adaptation. CCRA3 uses information on current and planned levels of adaptation to assess whether there is shortfall and assesses the benefits of additional adaptation to assess the urgency of action.

The needs and capacity for adaptation can be strongly influenced by the socioeconomic context. Net Zero has the potential to influence the exposure and vulnerability components of many of the risks assessed in CCRA3, since all sectors of the economy will be involved in the transition to Net Zero. Although detailed, specific information on Net Zero socioeconomic pathways is not yet available, the Climate Change Committee's assessment of potential Net Zero approaches (Climate Change Committee, 2019) provides broad information that is used in CCRA3 to make a first estimate of the implications for adaptation needs, potential and urgency.

During the course of conducting the CCRA3 assessment, socioeconomic conditions in the UK and around the world have suddenly been impacted by the Covid-19 pandemic. As well as potentially being influenced by the direct economic impact of the nationwide and near-global "lockdown" situations, the socioeconomic components of climate risks may also be influenced by measures and policies that may be designed to reinvigorate the economy. At the time of preparing the report, the implications of the pandemic for exposure, vulnerability and capacity for climate adaptation were only just beginning to emerge. They are included in the risk assessment to the extent that is possible, but this can only be regarded as preliminary.

## 2.6 UK and international perspectives

As well as assessing the risks and opportunities that climate change poses directly to the UK via potential impacts within its own geographical locality, CCRA3 follows CCRA2 in assessing the implications for the UK of current and potential climate change impacts elsewhere in the world. These international dimensions of climate change risk to the UK can include supply chains for food and other goods, migration and displacement, and security issues including the potential for conflict and humanitarian responsibilities. Both local and international risks and opportunities addressed in the assessment were selected through a process of consultation with stakeholders across various government departments.

### 3. Sources of evidence for CCRA3

#### 3.1 Evidence from the literature

A major source of information for CCRA3 is the literature in both peer-reviewed academic journals and non-academic reports from relevant organisations. The latter are often particularly important as sources of evidence on current and planned adaptation, and these are considered in the assessment if they have been subject to independent review.

While much of this evidence was brought in to the CCRA3 process through the knowledge of the literature of the author teams, further evidence was obtained via three open calls for evidence and through the review process. When assessing the magnitude of future risks, studies in the literature used climate projections from a large number of models with a variety of different emissions or concentrations scenarios. Wherever possible, the assessment used studies with projections aligning to the CCRA3 lower and higher scenarios of approximately 2°C and 4°C global warming at the end of the 21<sup>st</sup> Century, as defined in Section 2.3. Where the only available studies used projections with warming rates outside of the specified ranges of these pathways, expert judgement was used to establish the implications for changes within those pathways.

#### 3.2 New research for CCRA3

In addition, some research has been carried out specifically to feed into CCRA3, in order to address key knowledge gaps identified following CCRA2 and ensure that priority areas are informed by the most up-to-date evidence. Some of this was commissioned as part of the CCRA3 process, and some emerged from other research programmes such as the Met Office Hadley Centre Climate Programme and the Strategic Priorities Fund UK Climate Resilience programme of UKRI and the Met Office. Further details are provided in Chapter 2 (Watkiss and Betts, 2021).

#### 3.3 Using the latest UK Climate Projections

An important issue for the CCRA process is ensuring that the risk assessment considers all relevant climate projections, including the most recent, state-of-the-art projections. The latest set of UK Climate Projections (UKCP18; Lowe *et al.*, 2018) were published in 2018 with further components released in 2019 and 2020 and have been extensively used in the CCRA3 Technical Report and the research upon which it draws. UKCP18 global-scale probabilistic projections (Murphy *et al.*, 2018) have been used for defining the higher and lower scenarios of warming for framing the assessment of future risk magnitudes, as described in Section 2.3. The UK-scale probabilistic land projections (Murphy *et al.*, 2018), perturbed-parameter global and regional projections (Murphy *et al.*, 2018) and marine projections (Palmer *et al.*, 2018) underpinned the CCRA3 research carried out in support of the Technical Report (see Chapter 2; Watkiss and Betts, 2021), which directly informed the assessment of a number of risks. The high-resolution local projections (Kendon *et al.*, 2019) provided further context through the provision of improved assessment of extreme weather events, against which the conclusions of other research could be compared.

Not all risks were directly informed by UKCP18 because it can take some time – many months, and often years – for new projections to be used in scientific studies and for the results to be published in the peer-reviewed literature. To check the robustness of conclusions based on older projections, key results from UKCP18 were compared with equivalent results from the previous projections from UKCP09 (Murphy *et al.*, 2009) (Johns *et al.*, 2021).

The main focus was on aspects of the projections that used emissions scenarios that represent trajectories to approximately 2°C or 4°C global warming in the late 21<sup>st</sup> Century, as described in Section 2.3. Although the scenario of 4°C warming by the end of the century has been defined on the basis of the RCP6.0 emissions scenario, the range of results for the probabilistic projections overlap to some extent between the RCP, so some percentiles of other scenarios can also fall within the definition of the pathway to 4°C warming by the end of the century. For example, as well as including a large proportion of UKCP18 projections with RCP6.0 emissions, the 4°C warming scenario also includes the upper end of projections RCP4.5 emissions that warmed relatively fast due to high climate sensitivity. It also included the lower end of projections with RCP8.5 emissions that warmed relatively slowly due to low climate sensitivity (see for example Sayers *et al.*, 2020 and Arnell *et al.*, 2021).

In some cases, information relevant to 4°C global warming was only available from components of the UKCP18 that reached this level of warming faster than in the CCRA3 higher scenario, such as the majority of projections driven by the RCP8.5 emissions scenario. Where this involves quantities known to scale linearly with global warming levels, such as many aspects of extreme weather (Wartenberger *et al.*, 2017), it can be appropriate to treat such changes as representative of the regional climate state reached at the same level of warming at a later time (Bärring and Strandberg, 2018). In these cases, the changes projected at 4°C global warming were therefore applied to a later date within the range of the CCRA3 higher scenario (see for example HR Wallingford, 2020). This method was not applied for quantities which are strongly dependent on the rate of warming rather than its instantaneous magnitude, such as sea level rise. Higher-warming RCP8.5-based projections were also used to inform the general assessments of Low Likelihood High Impact scenarios described above.

## 4. Overview of the Technical Report chapters

Chapter 1 (Slingo, 2021) provides the climate science context for the risk assessment. It presents an update on observed climate change in the UK and across the world, including changes in the long-term climate state and extreme weather events and seasons. It provides a summary of the extent to which these changes are attributable to human-caused climate change and hence would be expected to increase further as human influence continues to grow. This is important information in the context of informing assessments of near-term risks. Since specific projections of the future consequences of current policies and global Paris-compliant policies are not available, Chapter 1 presents information available from the latest projections illustrating potential outcomes of these two categories of emissions futures. Chapter 1 also includes an overview of the implications for the standard projections of passing climate systems tipping points.

Chapter 2 (Watkiss and Betts, 2021) describes the methodology of the risk assessment and the steps taken by the authors in assessing the magnitude of risks, the effectiveness of current and planned adaptation and the benefits of additional action in the next 5 years, in order to assign the Urgency Score for each risk. Chapter 2 also summarises some of the key developments in evidence and understanding since CCRA2 was published, including lessons from other international risk, lessons learned from the CCRA2 process itself, and new understanding in climate science and adaptation, including improved evidence on vulnerability, exposure and adaptive capacity. It also includes a summary of the new or improved aspects of the CCRA3 method compared to CCRA2.

Chapters 3 to 7 present the assessment of risk and opportunity to the UK broadly categorised by general areas of policy or societal interest which illustrate how climate change is affecting all aspects of life in the nation. Natural Environment and Assets (Chapter 3: Berry and Brown, 2021) covers ecosystems, biodiversity, agriculture and the rural landscape, including the cultural landscape. Infrastructure (Chapter 4: Jaroszweski, Wood and Chapman, 2021) represents the physical assets that humans have constructed to support a modern, functioning society by providing protection from the elements, supplies of energy and water, and to facilitate transportation. Human Health, Communities and the Built Environment (Chapter 5: Kovats and Brisley, 2021) includes well-being, culture and homes of people as individuals or groups. Business and Industry (Chapter 6: Surminski, 2021) represents the economic operation of the country, and International Dimensions (Chapter 7: Challinor and Benton, 2021) reflects the critical, close relationship between the UK and the rest of the world. All these aspects of UK life are sensitive to weather and climate and have evolved or been designed in the context of historical conditions.

Chapters 3 to 7 represent risk categories that are identical to those in CCRA2 so provide continuity. However, some chapter titles have been updated to better highlight key areas of focus.

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## Annex 1. RCP emissions scenarios and projections consistent with current policies and ambitions.

**Table A.1** Projections of cumulative emissions from 2021 to 2100 for pre-2020 NDC commitments, and current policies as of 2016 with uncertainties, compared with the RCPs. RCP data are from <https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=compare>. Rogeli *et al.* (2016) (R16) provide 'Current policies' cumulative emissions for 2011 – 2100, from which cumulative emissions from 2021-2100 were derived by subtracting cumulative emissions from 2011-2020 (Friedlingstein *et al.*, 2020)

Emissions scenario / projection	Description	Reference	Cumulative emissions 2021 – 2100 (GtCO <sub>2</sub> )
RCP8.5	Standard emissions scenario associated with the RCP8.5 concentrations pathway.	van Vuuren <i>et al.</i> , (2011)	6629
Current Policies R16 – upper bound	Upper estimate of CO <sub>2</sub> emissions consistent with worldwide policies related to greenhouse gas emissions as of 2016, accounting for uncertainties in the CO <sub>2</sub> / non-CO <sub>2</sub> greenhouse gas mix and uncertainties in emissions trajectories after 2030.	Rogeli <i>et al.</i> , (2016)	4879
RCP6.0	Standard emissions scenario associated with the RCP6.0 concentrations pathway.	van Vuuren <i>et al.</i> , (2011)	3585
Constant emissions	Emissions remain at 2019 levels from 2021 to 2100.	Friedlingstein <i>et al.</i> (2020)	3446
Current Policies R16 – median	Median estimate of CO <sub>2</sub> emissions consistent with worldwide policies related to greenhouse gas emissions, as of 2016.	Rogeli <i>et al.</i> , (2016)	3090
Current Global Ambition CB6	Pre-2020 NDC commitments around the world in 2030 and continue to decarbonise at this same rate (changes in emissions intensity of GDP) after 2030. Prepared for the UK's 6 <sup>th</sup> Carbon Budget (CB6)	Vivid Economics and UCL (2020)	2855
RCP4.5	Standard emissions scenario associated with the RCP4.5 concentrations pathway.	van Vuuren <i>et al.</i> , (2011)	2423
Current policies R16 – lower bound	Lower estimate of CO <sub>2</sub> emissions consistent with worldwide policies related to greenhouse gas emissions as of 2016, accounting for uncertainties in the CO <sub>2</sub> /non-CO <sub>2</sub> greenhouse gas mix and uncertainties in emissions trajectories after 2030.	Rogeli <i>et al.</i> , (2016)	1950
RCP2.6	Standard emissions scenario associated with the RCP2.6 concentrations pathway.	van Vuuren <i>et al.</i> , (2011)	853

UK Climate Risk  
Independent  
Assessment (CCRA3)

# Technical Report

## Chapter 1: Latest Scientific Evidence for Observed and Projected Climate Change

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## Key Messages

This chapter considers the latest observations of, and future projections for, the changing climate in the UK and across the globe. In particular, this chapter focuses on new projections of climate change arising from developments in climate modelling since the 2<sup>nd</sup> Climate Change Risk Assessment (CCRA2) in 2017. These developments allow for a more comprehensive assessment of future UK and global climate changes, including those which might alter, materially, the range of risks and opportunities in the various sectors of this assessment compared to previous projections.

This chapter uses the term ‘climatic impact drivers’ to refer to changes in aspects of UK and global weather and climate (e.g., precipitation, temperature, etc). This distinguishes projected changes in aspects of the UK’s weather and climate from the hazards and opportunities that they drive (e.g., heavy rainfall changes driving changes in flooding hazard in some instances). This chapter also puts greater emphasis than in CCRA2 on assessing the variability of the UK’s weather and climate, and how this variability might change as the planet warms.

The main conclusions of this chapter are:

- 1. Since CCRA2 in 2017, the world has continued to warm with effects on UK and global weather and climate becoming more evident and increasingly attributed to human-induced climate change.** Temperature and sea level rise are the clearest signals of a changing climate for the UK. There is a growing body of evidence suggesting increases in mean rainfall, particularly in winter, and down the west side of the UK. The evidence base for whether UK storminess will change remains weak and should be addressed as a priority for future research.
- 2. New UK weather and climate records are being set more frequently, with the UK experiencing unprecedented high temperatures and heavy rainfall.** Extreme events test resilience and preparedness, and there is increasing evidence that, even today, human influences have changed and continue to change the likelihood of weather and climate extremes. New science since CCRA2 has highlighted that unprecedented extreme weather events are possible even in today’s climate; for example, there is currently a 1% chance every year that monthly winter UK rainfall can be 20-30% higher than the maximum observed.
- 3. The UK is projected to experience ongoing increases in temperature until the middle of the 21<sup>st</sup> Century under all scenarios for future global climate change, including those approximately consistent with achievement of the goal of the Paris Agreement to limit global warming to well below 2°C.** Until the middle of the century, the extent and spatial pattern of UK climate change depends more on regional climate and weather responses to global warming than the level of future global greenhouse gas emissions.
- 4. From the 2050s onwards, higher emissions scenarios are projected lead to greater increases in extreme weather and sea level both at UK and global scales.** In a high scenario by 2080, 40°C is projected to be exceeded as frequently as 32°C is exceeded today. At the time of this assessment 40°C has not yet been reached in the UK, but could occur with a return time of 3.5 years by the end of the century in a high-warming scenario.

5. **The severity of extremes is projected to increase with global warming.** Meteorological, agricultural and hydrological droughts are expected to become more severe with implications for water resource management. An increase in the incidence of high summer daytime temperatures throughout the UK. In the future, Scotland and Northern Ireland could start to see high summer temperatures similar to those of England and Wales currently. All parts of the UK will continue to experience a steady reduction in frost days as global warming increases, although some years will still see similar numbers of frost days and cold-related impacts as in recent years.
6. **Future summers are projected to be even hotter and drier than earlier estimates in CCRA2, for equivalent levels of global warming.** Based on the new Met Office models in the UK Climate Projections 2018 (UKCP18), reductions in future rainfall are substantially larger over England, typically double those used in CCRA2. This is due to improved simulations of summer circulation anomalies and their impacts on rainfall, as well as higher temperatures. However, year-to-year variations in summer rainfall indicate that while drier summers are generally more likely across the UK, wetter summers are also possible. Furthermore, despite overall summer drying, with wet days projected to become less frequent, the new kilometre-scale projections suggest that when it does rain, the daily rainfall will be more intense by as much as 20%, relative to coarser models.
7. **We can expect more frequent and more severe extreme daily high temperatures and Urban Heat Island effects even though the mean warming is almost identical.** Better representation of the landscape and urban areas in the kilometre-scale model have highlighted that there is a very small chance (less than 0.02%) of exceeding 40°C by 2040, but by 2080 the frequency of exceeding 40°C is similar to the frequency of exceeding 32°C today. Urban heat island intensity will increase during both day and night, but new results have shown greater increases in night-time intensities implying significantly more 'tropical nights'. During summer, night-time temperatures in the urban areas of 10 major cities will increase significantly, at rates between 0.48 and 0.55°C per decade during the 21<sup>st</sup> century.
8. **New kilometre-scale projections show pronounced shifts to more intense hourly rainfall at the expense of lighter rainfall, compared with coarser models as used in CCRA2.** For example, summer hourly extremes of 20mm/hour may occur twice as frequently as previously projected. Furthermore, there is new evidence on the frequency of rainfall exceeding 30mm/hour for some UK cities, showing that such events are twice as likely by 2080.
9. **Winter extreme rainfall is projected to be around 40% more intense compared to CCRA2, with future winters becoming warmer and wetter overall.** New kilometre-scale projections from UKCP18 shows that physical processes not resolved in the coarser regional and global models increases projections for future winter rainfall by around 40% relative to previous projections. They also show that daily rainfall intensity is projected to increase by as much as 25% relative to coarser models, particularly in the south-east.

- 10. Future winter weather is projected to be dominated by more mobile, cyclonic weather systems than was the case in previous assessments.** This will affect the western parts of the UK, in particular, and reinforces the evidence for more substantial increases in daily rainfall with related flooding, as well as a higher incidence of strong winds and waves. The projected shift to more mobile, cyclonic winters may also increase the risk of atmospheric river events that bring large amounts of rainfall and are major contributors to severe flooding and landslides, particularly for the mountainous regions of the UK.
- 11. The increase in rainfall intensity and mobility of cyclonic weather patterns arise from improvements in climate modelling.** Although the HadGEM3-GC3.05 model used for these components of the UKCP18 projections has a very high climate sensitivity, these results for rainfall intensity and storminess are not related to that process. The UKCP18 probabilistic projections do not use HadGEM3-GC3.05 – instead, they use the same base model as the UKCP09 projections, plus a wider consideration of the large set of multi-model projections in the 5<sup>th</sup> Coupled Model Intercomparison Project (CMIP5). The UKCP18 probabilistic projections warm faster than the CMIP5 projections because they include uncertainties in carbon cycle feedbacks.
- 12. New estimates of global sea-level rise indicate an additional 5 - 10cm rise by 2100 compared with CCRA2 estimates.** These include a contribution from Antarctic ice dynamics. These faster projections of sea level rise are due to improved understanding and modelling of land ice processes, not faster warming due to higher climate sensitivity, because the new sea level projections are being driven by the CMIP5 projections rather than the UKCP18 land projections.
- 13. Low-likelihood, high-impacts scenarios are considered in CCRA3.** The new regional projections warm faster than those used in CCRA2, partly due to high climate sensitivity in the global model, and partly due to the use of a higher emissions scenario. Therefore the timing of these regional changes should not be considered the most likely outcome but factored into planning as a lower probability high risk future. In the most extreme sea level scenarios, global sea-level rise could reach 2m by 2100 but this is viewed as very unlikely and with low confidence. However, the processes behind ice sheet collapse particularly for Antarctica remain very uncertain and continued monitoring and process studies are vital.

Scientific advances since CCRA2, along with the delivery of UKCP18 and the development of a new generation of climate models, have provided new and important evidence regarding expected changes in the UK's weather and climate. This chapter summarises a significant body of new evidence on projected changes in the UK's weather and climate that will help improve assessment of future climate risks and opportunities. In particular, the most up-to-date and physically comprehensive projections indicate that future changes may be more extreme than previously projected in CCRA2, especially locally and on daily timescales. In some areas, important knowledge gaps remain, for example, further research is required to test the robustness of projections in changes in storminess.

## 1.1 Introduction

This chapter summarises the latest scientific evidence on current and future climate change, including new advances made since the second climate change risks assessment (CCRA2), which either consolidate previous understanding or bring new insights. These assessments will be placed in the context of global changes, especially where these changes may have a material impact on the UK.

CCRA2 drew on literature assessing future climatic impact drivers for the UK and worldwide based mainly on the United Kingdom Climate Projections 2009 (UKCP09) and the global projections published in the IPCC Fifth Assessment Report (AR5). These projections have also informed much of the literature available for assessment in CCRA3.

Whilst the IPCC Sixth Assessment Report (AR6) has not yet been published, a new set of UK Climate Projections (UKCP18) has been published since CCRA2. These projections draw on significant advances in model development since the earlier UKCP09 and IPCC AR5, as well as research conducted in preparation for the creation of new sets of climate projections in the 6<sup>th</sup> Coupled Model Intercomparison Project (CMIP6). CMIP6 underpins the IPCC 6<sup>th</sup> Assessment Report, due to be published in July 2021.

This chapter will focus specifically on identifying significant differences in the climate science evidence base from UKCP09 and CCRA2, drawing on the results from UKCP18 in particular. Since CCRA2 there have been important scientific advances across a number of fronts:

- Extended observational records through data archaeology and improved global and regional reanalyses, including additional recent observations during a time of global warmth unprecedented in the observational record.
- Ongoing detection and attribution of climate change trends in the observational record, and the rapidly developing methodologies for attributing extreme events to human-induced climate change.
- New global and UK regional projections based on improved modelling systems with higher resolution and better representation of climatic impact drivers, especially associated with climate variability, weather systems and local extremes.
- Greater overall understanding of the climate system, its response to forcing, and the potential for accelerating Earth system feedbacks and abrupt changes.

It is widely recognised that some of the more costly, disruptive and dangerous impacts of climate change will be associated with increased frequency and/or intensity of extreme weather and climate events. The UK's weather and climate are highly variable because of where the country sits on the globe - at the end of the North Atlantic storm track where cold polar and warm sub-tropical air masses collide, and with maritime influences from the ocean to the west, and continental influences from Europe to the east. These factors make detecting, attributing, predicting and projecting changes in UK's weather and climate, especially for more extreme events, challenging, but vitally important.

Consequently, this chapter puts greater emphasis on assessing the variability of the UK's weather and climate, how this variability might change in terms of frequency and/or intensity as the planet warms, and what this means for unprecedented extremes and their impacts. This has been made possible by significant advances in global and regional climate modelling and their applications since

UKCP09 and CCRA2, with current climate models now able to capture regional and local weather with greater fidelity. These advances are documented in Annex 1 and include significant increases in global model resolution for both the atmosphere (60km spacing between grid cells, reduced from 150km in CCRA2) and oceans (0.25° from 1° in CCRA2), improvements in the model physics, increases in regional model resolution from 25km to 12km, and the deployment of a new kilometre-scale UK regional model.

Although the socio-economic impacts of climate change will be felt more keenly through extreme weather and climate events, the natural environment is also susceptible to longer-term trends in the climate, such as shifts in the regular seasonal weather and climate conditions, which affect phenology, habitats and survival of species. These impacts may only come into play, or become serious, when certain meteorological thresholds are exceeded. Consequently, as part of CCRA3, additional analysis of UKCP18 has been carried out to provide information on, firstly, the changes to weather and climate variability and extremes, and secondly, on trends in climatic indices that affect the natural environment.

## 1.2 Our approach to assessing the new climate science that underpins CCRA3

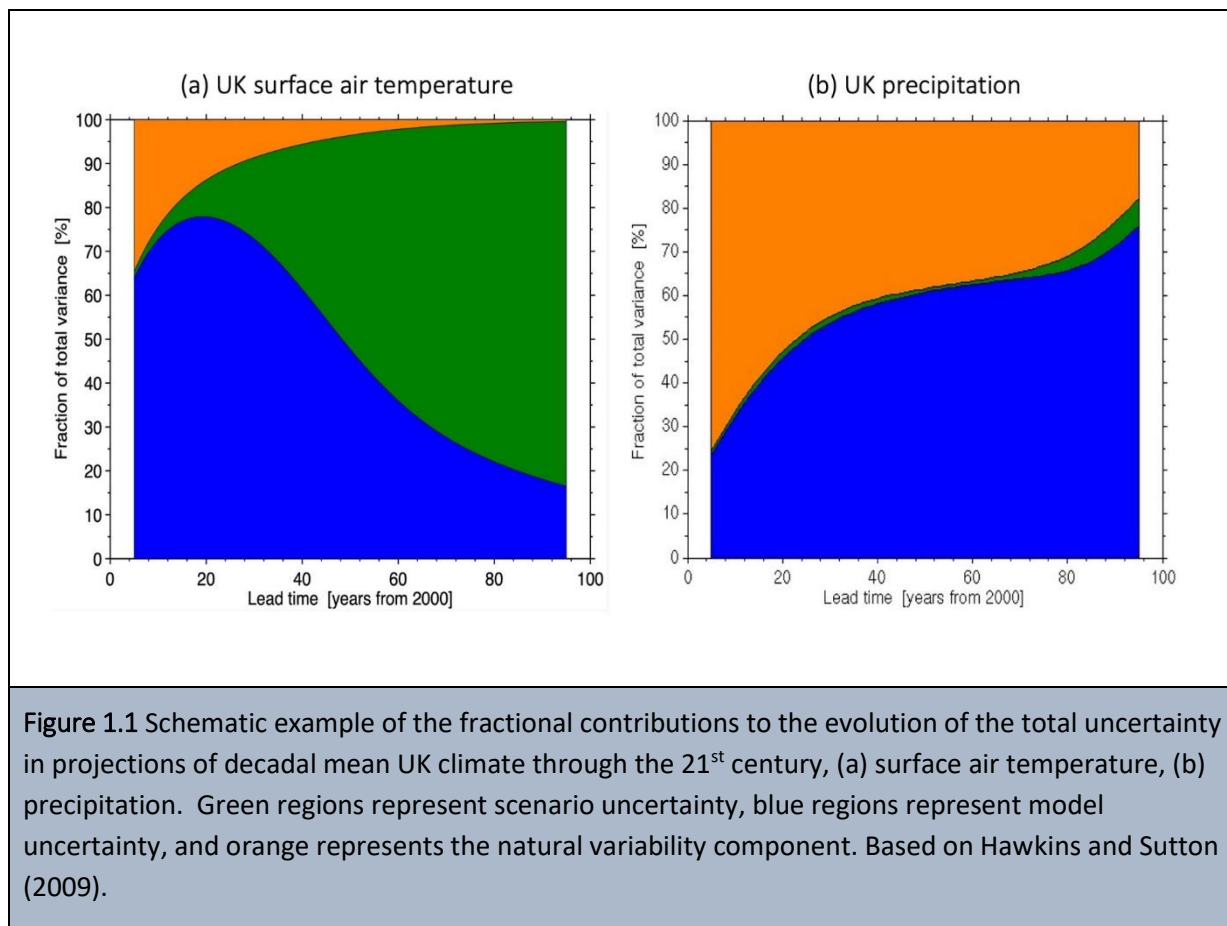
As with the sectoral chapters and documented in Chapter 2, the approach here is to integrate existing information from the literature base and previous projections, with new projections and other new research. UKCP18 has provided important new evidence and much of the chapter will focus on how this has evolved our understanding of the UK's future climate. CCRA3 uses all the UKCP18 products to some extent, mainly the probabilistic projections and HadGEM3 global projections, but also the regional and local projections where possible.

### 1.2.1 Representing uncertainty in the new UKCP18 projections

It is essential that we consider the uncertainty in the climatic impact drivers by looking at the various sources of uncertainty, how they evolve with time through the 21<sup>st</sup> century (Figure 1.1 based on Hawkins and Sutton, 2009), and how well the various ensembles of global and regional projections are able to sample the range of possible outcomes. It is also important to understand that different climatic impact drivers have different sources of uncertainty. As Figure 1.1(a) shows, surface temperature change is dominated by natural (internal) variability<sup>1</sup> for the first 2 decades whilst the uncertainty due to the global emission scenarios remains relatively small. For the latter half of the century, the uncertainty is increasingly dominated by the global emission scenarios. Model uncertainty, associated for example with cloud feedbacks, is important throughout. On the other hand, for precipitation (Figure 1.1(b)), natural variability plays a significant role at all lead times whilst scenario uncertainty barely enters the assessment.

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<sup>1</sup> Natural variability describes the variations in weather and climate that we experience from day-to-day, year-to-year and decade-to-decade. They occur due to internal processes in the climate system associated with the atmospheric (such as weather patterns) and oceanic circulation (such as El Niño). They also include intermittent impacts from explosive volcanic eruptions and associated cooling by aerosols.



The UKCP18 projections include a number of components using different sets of models and different approaches to quantifying or exploring uncertainty (Murphy *et al.*, 2018):

- (i) the probabilistic land projections (at UK and global scales) with a range of emissions scenarios.
- (ii) perturbed-parameter ensembles of global, regional and local projections (at resolutions of 60km, 12km and 2.2km respectively) with a very high emissions scenario
- (iii) derived projections representing long-term climate states at 2°C and 4°C global warming and a low-emissions scenario
- (iv) marine projections.

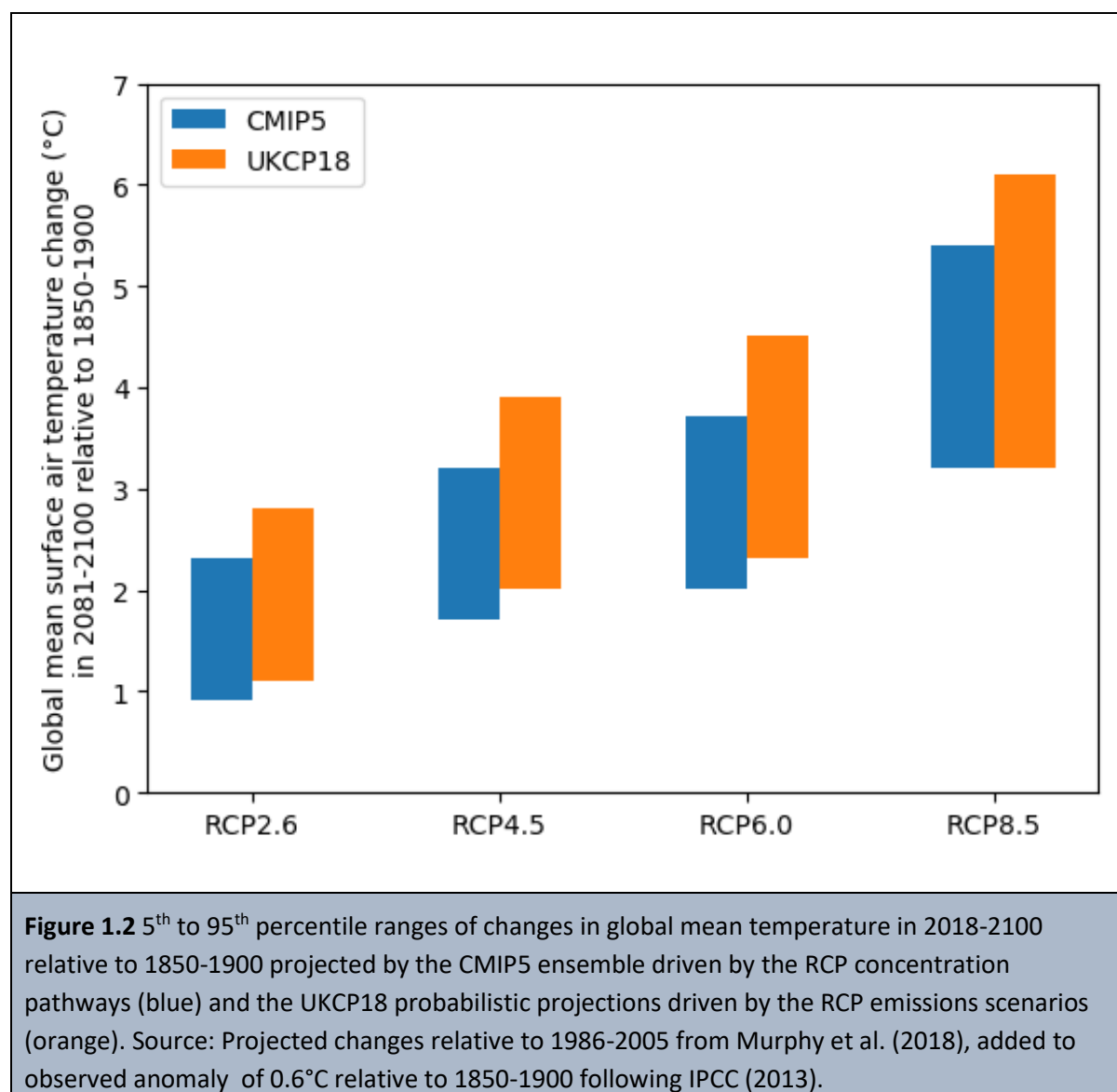
The probabilistic projections are based on the same climate model, HadCM3, as used in UKCP09, with additional information from the CMIP5 multi-model ensemble. These provide a comprehensive quantification of uncertainty, drawing on this very wide base of information including a large number of independent models. The global perturbed-parameter ensemble (PPE) uses the HadGEM3-GC3.05 climate model, and the regional and local ensembles use high-resolution limited area models taking boundary conditions from the global PPE. The derived projections use the HadGEM3-GC3.05 PPE and CMIP5. The marine projections use CMIP5, applying these to new models of sea level rise and other aspects of marine impacts. The use of different sets of models in the various strands of UKCP18 arose from the need to carry out developments in all strands in parallel. The final set of projections are all useful for different aspects of climate change risk assessment and are all used in CCRA3 in various places. Since they use different models and different

approaches, use of several strands together requires an awareness of potential inconsistencies. The following chapters in the CCRA3 Technical Report make clear which UKCP18 strands have been used, and also whether other sources of climate projections have been used.

UKCP18 uses emissions scenarios linked to the Representative Concentration Pathways (RCPs), with an important feature being the representation of uncertainties in carbon cycle feedbacks. This contrast with the CMIP5 ensemble, in which all models are driven by the same concentration pathway for CO<sub>2</sub> and other greenhouse gases (see Annex 1 section A1.4 for discussion of the important difference between the RCPs used as Concentration Pathways and Emissions Scenarios). The probabilistic projections considered four RCP scenarios, ranging from RCP2.6 (which is consistent with extensive mitigation of emissions) through to RCP8.5 (which has future emissions considerably higher than pathways considered consistent with current worldwide energy policies). The intermediate scenarios RCP4.5 and RCP6.0 were also included: these are within the range of possible emissions futures considered consistent with current worldwide policies. In CCRA3, RCP6.0 is used to define the higher climate change scenario used for the risk assessment. Many, but not all, projections with RCP8.5 are considered as low-likelihood, high-impact outcomes and not included in the main assessment. Details of the use of the different emissions scenarios and concentration pathways are given in the Introduction chapter (Betts and Brown, 2021), and Chapter 2 (Watkins and Betts, 2021).

Comparing the UKCP18 global probabilistic projections at 2081-2100 relative to 1850-1900 with those from CMIP5 for the RCP scenarios, UKCP18 projects ranges of global warming which are systematically higher than those of CMIP5 (Figure 1.2). A major factor contributing to this difference is that the CMIP5 projections were driven by CO<sub>2</sub> concentrations from the standard RCP pathways, whereas UKCP18 used emissions scenarios associated with the RCPs, accounting for uncertainties in climate-carbon cycle feedbacks. For each emissions scenario, UKCP18 therefore represented the response to a range of CO<sub>2</sub> concentration pathways, most of which were higher than the standard pathways (Murphy *et al.*, 2018). Further details are given in Annex 1 section A1.4.





Due to the computational cost of the new high resolution regional simulations for UKCP18 (see Annex 1), the UK regional and local climate change scenarios were only produced using a single emission scenario to allow for the largest possible ensemble size to be utilized, in order to cover a wide range of regional climate responses. The highest emissions scenario, RCP8.5, was chosen so that the widest range of future levels of global warming could be explored, including the most extreme climate changes considered as low-probability, high-impact scenarios. This means that, unlike the probabilistic projections, the HadGEM3 global projections and associated regional and local projections are not available for RCP6.0, RCP4.5 and RCP2.6 which project slower rates of warming than RCP8.5. Nevertheless, for many climate impact drivers, the projected regional changes at particular levels of global warming can be considered to be representative of the same level of global warming reached at a later date with a lower emissions scenario and/or as a result of a lower climate sensitivity.

CCRA3 is framed in terms of trajectories of global warming rather than emissions scenarios. Research commissioned on some of the risks therefore used selected components of the UKCP18 projections representing global warming of approximately 2°C and 4°C at the end of the century. The assessment of other risks draws on literature using other models, projections and scenarios that give approximately 2°C and 4°C global warming by 2100.

### 1.2.2 Improved regional dynamics for the simulation of UK weather and climate in the new UKCP18 projections

Hazardous weather with the potential to cause harm, such as floods and heatwaves, have always occurred due to weather and climate variability, but their frequency and / or magnitude can be affected by anthropogenic climate change. Although climate change is often quantified in terms of global mean surface temperature (GMST), the impactful changes at local scales depend on complex responses of the climate system to greenhouse gas increases, and the interactions between these responses and the processes of climate variability (Sutton *et al.*, 2015). GMST primarily provides information about the level of aggregated global risks from climate change and is the main metric for efforts to reduce global emissions. On the other hand, understanding and quantifying natural variability and the complex response of the global circulation to anthropogenic warming is essential for projecting climatic impact drivers on regional to local scales.

The UK's weather and climate, especially precipitation, are dominated by natural variability and will continue to be so. In this regard, the position and variability of the North Atlantic Jetstream is of fundamental importance for determining the weather and climate of the UK, and its future behaviour will define many of our future climatic impact drivers.

The behaviour of the North Atlantic Jetstream is particularly complicated, compared, say, with the Pacific Jet. In winter, it has three preferred positions with each position corresponding to specific weather regimes – to the north of the UK (European Blocking), over the UK (positive North Atlantic Oscillation) and to the south of the UK (negative North Atlantic Oscillation). These regimes describe the tracks of storms and the development of blocking episodes, and essentially determine the frequency and/or intensity of windstorms, atmospheric rivers<sup>2</sup> and extreme frontal rainfall.

Consequently, a focus of this chapter is on how the North Atlantic Jetstream may behave in the future and what this means for the key weather regimes that define the UK's winter climate. To do this, it is important that global climate models can capture the three positions of the Jetstream described above, and to do it for the right reasons.

Since CCRA2, the Met Office has made significant advances in global and regional modelling for weather and climate prediction. A new climate model, HadGEM3, has been developed which features significant increases in horizontal and vertical resolution in the atmosphere and ocean, as

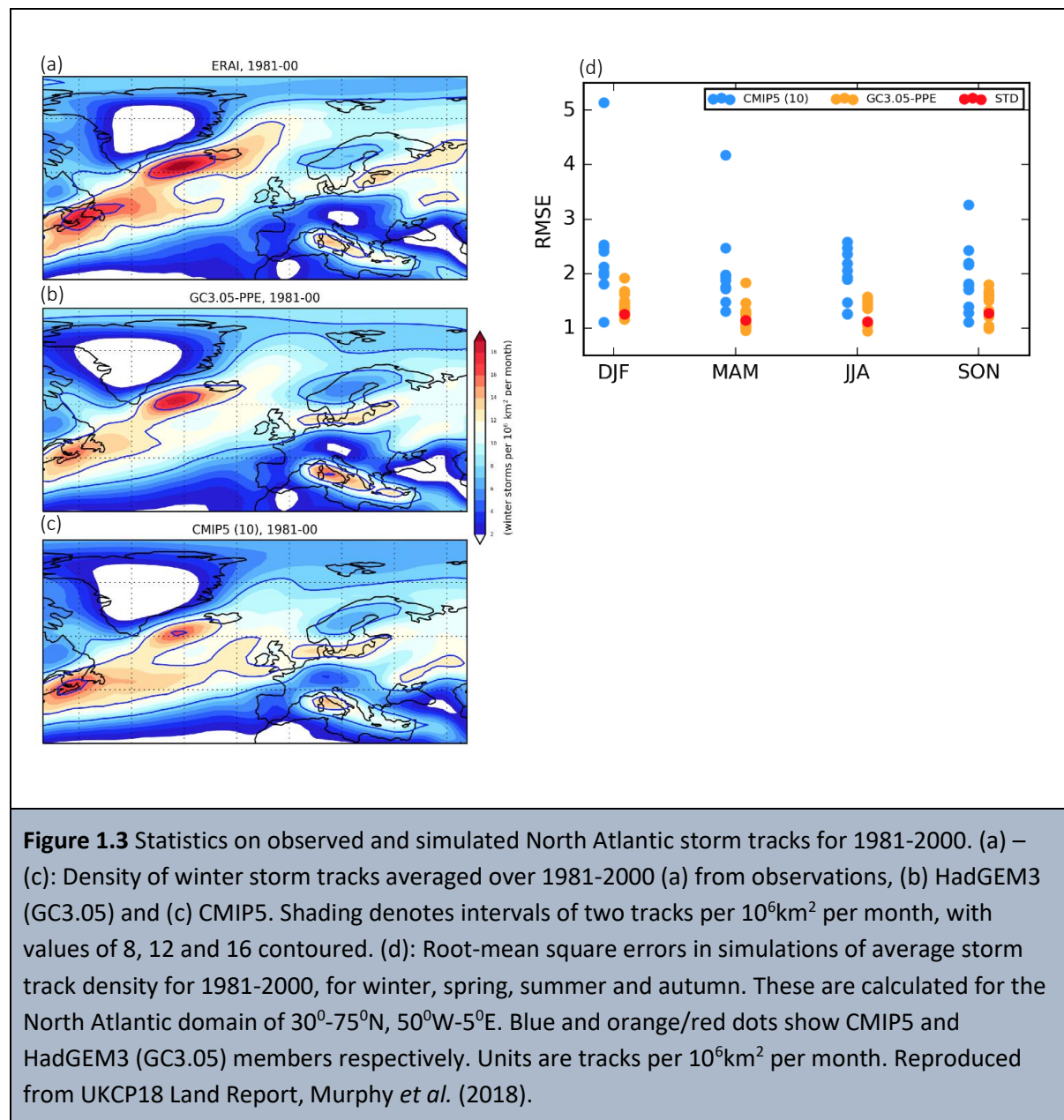
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<sup>2</sup> Atmospheric rivers are relatively long, narrow regions that form on a strong jet stream and are characterized by intense moisture transport, which, on landfall, produce excessive precipitation that can lead to major flooding (e.g., Lavers *et al.*, 2011). Storms Desmond and Dennis in 2015 and 2020, respectively, are examples of atmospheric river events.

well as improvements in model physics (Williams *et al.*, 2018). The atmosphere model resolution increased from 150km in the horizontal, as used for CMIP5 and IPCC AR5, to 60km, and from 38 to 85 levels in the vertical. The ocean resolution increased from 1° to 0.25° and from 40 to 75 levels. These enhancements in resolution have delivered significant improvements in the structure of weather systems and ocean circulation, giving notable reductions in a number of key systematic model biases (Annex 1 and Figure A1.1 from Murphy *et al.*, 2018).

Of particular relevance to CCRA3, is the improvement in the simulation of the position and variability of the North Atlantic Jetstream in HadGEM3, and hence the weather systems that affect the UK (Figure 1.3). Figure 1.3 (a-c) shows the density of the tracks of winter storms over the North Atlantic for 1981 to 2000 from the observations (ECMWF Reanalyses) and from the ensemble means of the HadGEM3 (GC30.5-PPE) and CMIP5 simulations; Figure 1.3(d) provides a summary of the seasonal errors in simulated track density.

HadGEM3 reproduces observed winter storm track density quite well in general, whereas the CMIP5 models tend to underestimate the maximum south of Greenland and the observed extension to the north-east of Iceland is missing. Of particular relevance to CCRA3, the number of storms tracking across the UK and into Europe is overestimated in the CMIP5 models. Seasonal error statistics (Figure 1.3(d)) typically show a larger spread of errors for the CMIP5 models, and several CMIP5 members score worse than any of the HadGEM3 members, in each of the four seasons. One CMIP5 model shows root mean squared error (RMSE) values considerably larger than the other simulations in winter, spring and autumn, because the storm track is shifted south and is too zonally (east-west) oriented, with too many winter storms moving across the UK and western Europe. Further background information on the Jetstream in HadGEM3 and the CMIP5 models can be found in McSweeney and Bett (2020).



As part of major advances in seasonal to decadal prediction<sup>3</sup> using HadGEM3 (e.g., Scaife *et al.*, 2014; Smith *et al.*, 2019), there has been significant progress recently in understanding the global drivers of the UK's climate variability and associated weather regimes. These include the El Niño/Southern Oscillation (ENSO), drivers from the stratosphere such as stratospheric sudden warmings, and the patterns of sea surface temperatures in the North Atlantic. These advances play an important role in assessing how the global effects of climate change on phenomena, such as

<sup>3</sup> There is an important distinction between prediction and projection. Prediction starts from an observed initial state of the weather and climate system and aims to forecast how the climate system will evolve in the coming days to years (such as in numerical weather prediction and monthly to decadal climate prediction). Projection is simply a simulation of how the climate system might behave in response to changing imposed external forcings such as greenhouse gas and aerosol concentrations.

ENSO, might alter the population of the three positions of the Atlantic Jetstream shown in Figure 1.2 and hence on UK weather regimes. Improvements in predictability give us confidence that HadGEM3 has captured natural climate variability and its drivers more faithfully.

HadGEM3 is part of the comprehensive new set of UK climate projections (UKCP18) and other applications, including global forecasts on timescales of months to a decade ahead. The UKCP18 regional and local projections (see UKCP18 Science Reports – Murphy *et al.*, 2018; Palmer *et al.*, 2018; Kendon *et al.*, 2019), all used HadGEM3, with the boundary conditions<sup>4</sup> coming from variants of that model. As documented in detail in Annex 1, HadGEM3 brings some important benefits to our assessment of future climatic impact drivers for the UK.

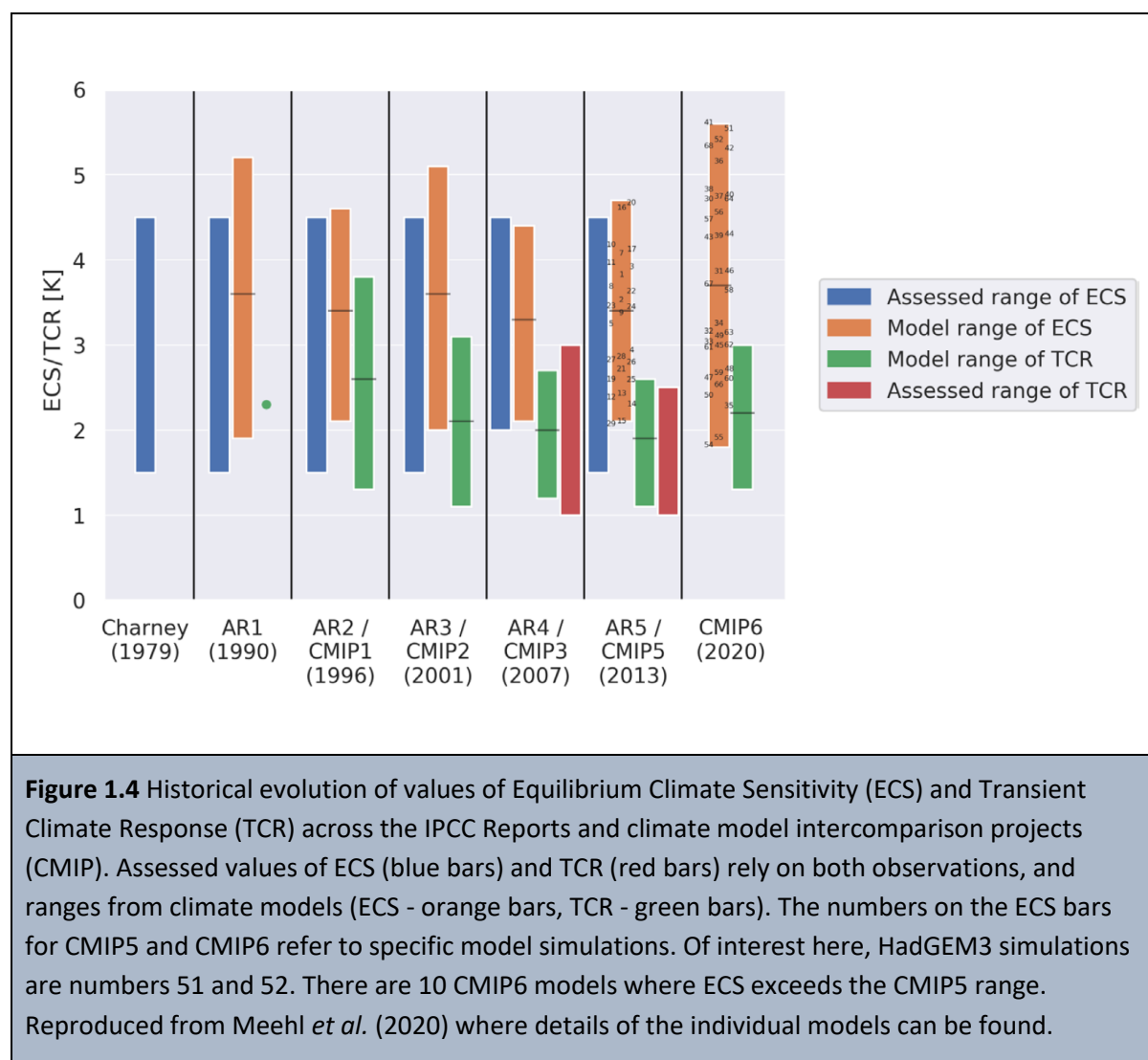
In summary, HadGEM3 has delivered significant improvements in simulating the observed variability of the North Atlantic Jetstream in terms of both its latitudinal position and the temporal frequency of each preferred location. This means that UKCP18 results based on HadGEM3 are likely to provide a more reliable evidence base for changes in the UK's weather and climate, many of which will depend on how natural climate variability will change and not just on the overall warming.

### 1.2.3 Climate sensitivity in the new UKCP18 projections

The CMIP5 models already cover a wide range of climate sensitivities. However, the climate sensitivity of new Met Office global model, HadGEM3, submitted to CMIP6 lies outside the upper range of the CMIP 5 models. HadGEM3's Equilibrium Climate Sensitivity (ECS) of 5.4°C from preindustrial levels for a doubling of atmospheric CO<sub>2</sub> concentrations can be compared with an ECS of 4.6°C for the earlier version of the Met Office model used in CMIP5. This is higher than in all climate models from previous generations used in the CMIP3 and CMIP5 intercomparison projects (Figure 1.4), but consistent with a sub-set of other recently developed climate models submitted to CMIP6 (Andrews *et al.*, 2019; Forster *et al.*, 2020; Meehl *et al.*, 2020). The causes of the higher ECS in these new climate models are currently being studied in detail, with cloud feedbacks and cloud-aerosol interactions in models with prognostic aerosol schemes seeming to be playing an important role. Zelinka *et al.* (2020) showed that this increase in ECS was primarily associated with stronger positive cloud feedbacks from decreasing extratropical low cloud coverage and albedo in this sub-set of models compared to the corresponding models in the previous generation.

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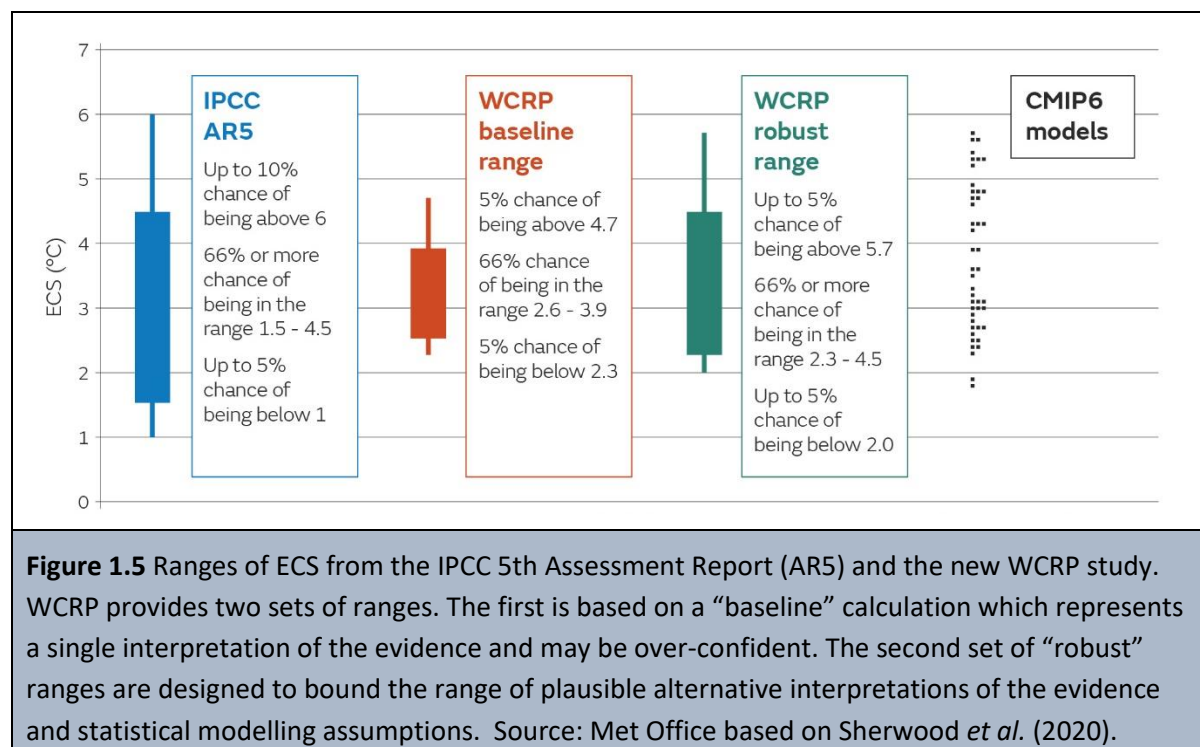
<sup>4</sup> Boundary conditions refer to the time-varying atmospheric conditions that enter the regional model domain and come from the global climate model in which the regional model is embedded. This means that, to a large extent, the regional model is 'slave' to the global model's simulation of weather and climate variability; this is why the choice of global driving model is so important.



As increased climate sensitivity increases projected global warming under future emissions scenarios, establishing the plausibility of these higher sensitivity models is imperative given the potential implications for climate risk assessments. In 2015, the World Climate Research Programme (WCRP) commissioned a major international study to explore whether it is possible to constrain the estimates of ECS using the latest evidence including (i) feedback process understanding, (ii) the historical climate record, and (iii) the paleoclimate record. A summary of the results of this comprehensive study (Sherwood *et al.*, 2020) is shown in Figure 1.5.

The most important result is that it is impossible to reconcile sensitivities less than 2°C from these three strands of evidence; indeed, this new study suggests that the "likely range" (>66% probability range) has narrowed to, at most, 2.3°C to 4.5°C - or possibly an even narrower range of 2.6°C to 3.9°C when all lines of evidence are considered. The lower end of this range is increased substantially from the 1.5°C lower bound in IPCC AR5, meaning that scientists are now much more confident that global warming will not be small.

In addition, according to Sherwood *et al.* (2020), there is up to an 18% chance that ECS is above 4.5°C, but no more than a 5% chance that it is above 5.7°C. So, while HadGEM3 is at the high end of these estimates, its ECS cannot be eliminated by other lines of evidence.



Another way to assess the plausibility of a model’s climate sensitivity is to test its skill in weather forecast mode, as advocated by Rodwell and Palmer (2007). This is not widely attempted because very few climate models are also run as weather forecasting models, with the UK Met Office being unusual in this respect. Williams *et al.* (2020) describe tests of HadGEM3 in weather forecast mode, in which they investigated the validity of the model changes responsible for increasing the climate sensitivity. The results showed that these model changes improved the short-range weather forecast and reduced the error growth over the first few hours of the forecast. This suggests that the physical processes represented by these model changes may be a more accurate representation of the real world, and so it is not possible to dismiss completely the high ECS of HadGEM3 as a plausible possibility.

ECS is an idealized quantity that reflects the very long-term (150 years plus) response of the Earth System to a constant forcing of double CO<sub>2</sub>. Transient Climate Response (TCR; warming at the time of CO<sub>2</sub> doubling in an idealized 1% per year increase in atmospheric concentration scenario) is a better measure of warming over the near- to medium-term and therefore more relevant to climate adaptation.

Figure 1.4 highlights that although the upper end of the ECS has increased substantially in CMIP6 compared to CMIP5, the distribution of TCR has not changed as much. HadGEM3’s TCR (2.6°C) is slightly higher than in some CMIP6 models, but only up from 2.5°C for the corresponding model in CMIP5 (Meehl *et al.*, 2020). Again HadGEM3’s TCR is in the upper part of the CMIP6 range and therefore means a greater rate of global warming compared to that simulated in CMIP5 models,

especially through the latter half of the 21<sup>st</sup> century; this affects the rate of warming at UK scales as well. This indicates that, for the latter half of the 21<sup>st</sup> century, HadGEM3 will generate UK warming at the upper end of the range from previous assessments and will challenge us on how to evolve the risk assessments from CCRA2 to CCRA3.

It would be unwise though, on the basis of this higher sensitivity, to de-emphasise the HadGEM3-related regional and local climate projections from UKCP18. As has already been shown, HadGEM3 is a more skilful model in terms of the mean climate and its variability, especially for the Euro-Atlantic sector and the weather patterns that affect the UK, and consequently may provide a more robust assessment of future changes in high-impact or extreme weather and climate events that are fundamental for UK adaptation and risk assessments. Furthermore, the effects of this high climate sensitivity can be minimised if we consider risks at specific global warming levels rather than time horizons through the 21<sup>st</sup> century. Consequently, we have used both approaches in the following assessment of future climate impact drivers. Generally the HadGEM3 temperature trajectory should be interpreted as a high impact, low probability future but any temperature-level analysis should be considered to be unaffected by climate sensitivity. In this chapter we note when conclusions are affected by the model's high climate sensitivity but generally focus on the robust conclusions that would remain true if the model were to have a lower climate sensitivity.

## 1.3 Climate change that has already occurred

This section summarises the latest evidence that has been accumulated since CCRA2 on the climate change that has been observed across the UK and globally. Each year the Met Office publishes its annual 'State of the UK Climate' (e.g., Kendon *et al.*, 2020), which provides a comprehensive analysis of the latest observational records. Since CCRA2, several UK climate records have been extended further into the past through data archaeology, recovery and digitising of past weather records. UK-wide temperatures now go back to 1880 and rainfall to 1862, both on a 1 km grid (HadUK-Grid; Hollis *et al.*, 2019), and there will be further progress in reconstructing historical weather and climate records for CCRA4. There is also more information on finer timescales (daily and even sub-daily), which is enabling much greater understanding of past extremes.

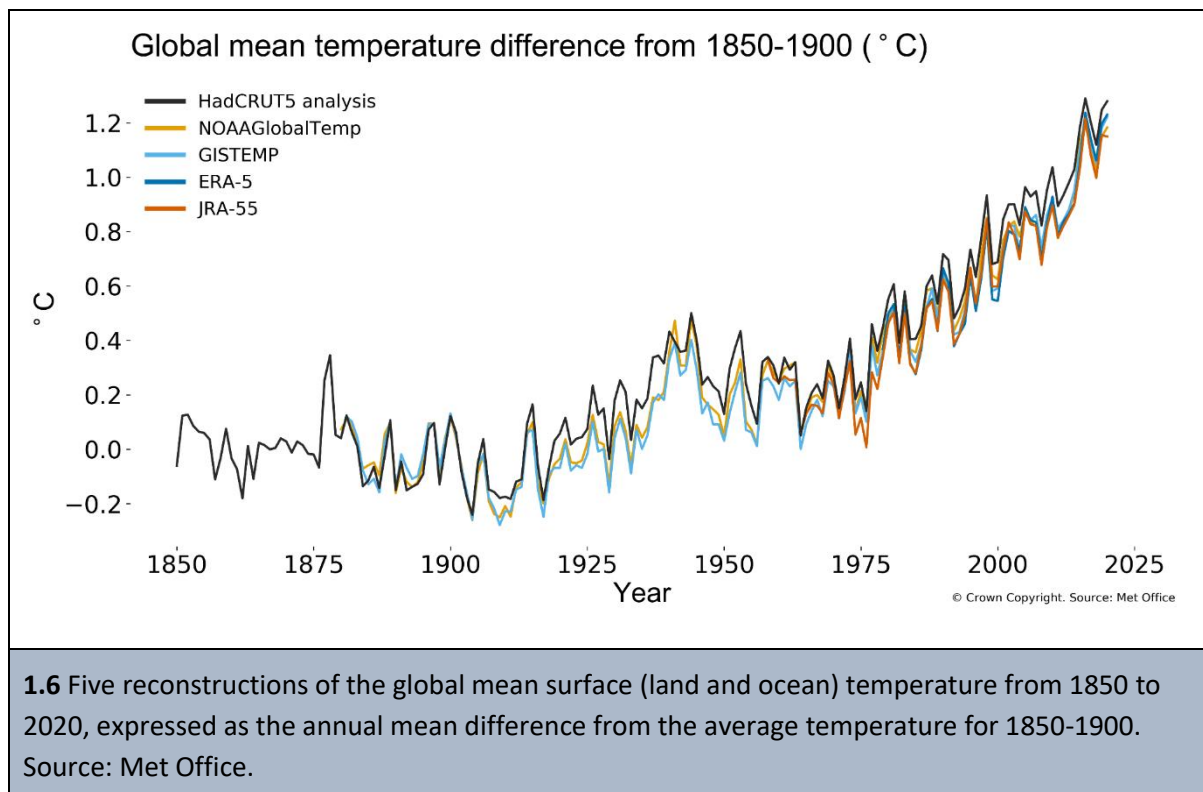
The UK record can be placed within the context of changes in global and European climate, which are now routinely documented in the annual WMO Statement on the State of the Global Climate (WMO, 2019), the international annual assessments by the American Meteorological Society (Blunden and Arndt 2019) and the European State of the Climate (ESOTC) annual report compiled by the EU Copernicus Climate Change Service (ESOTC, 2019).

### 1.3.1 Temperature and Heatwaves

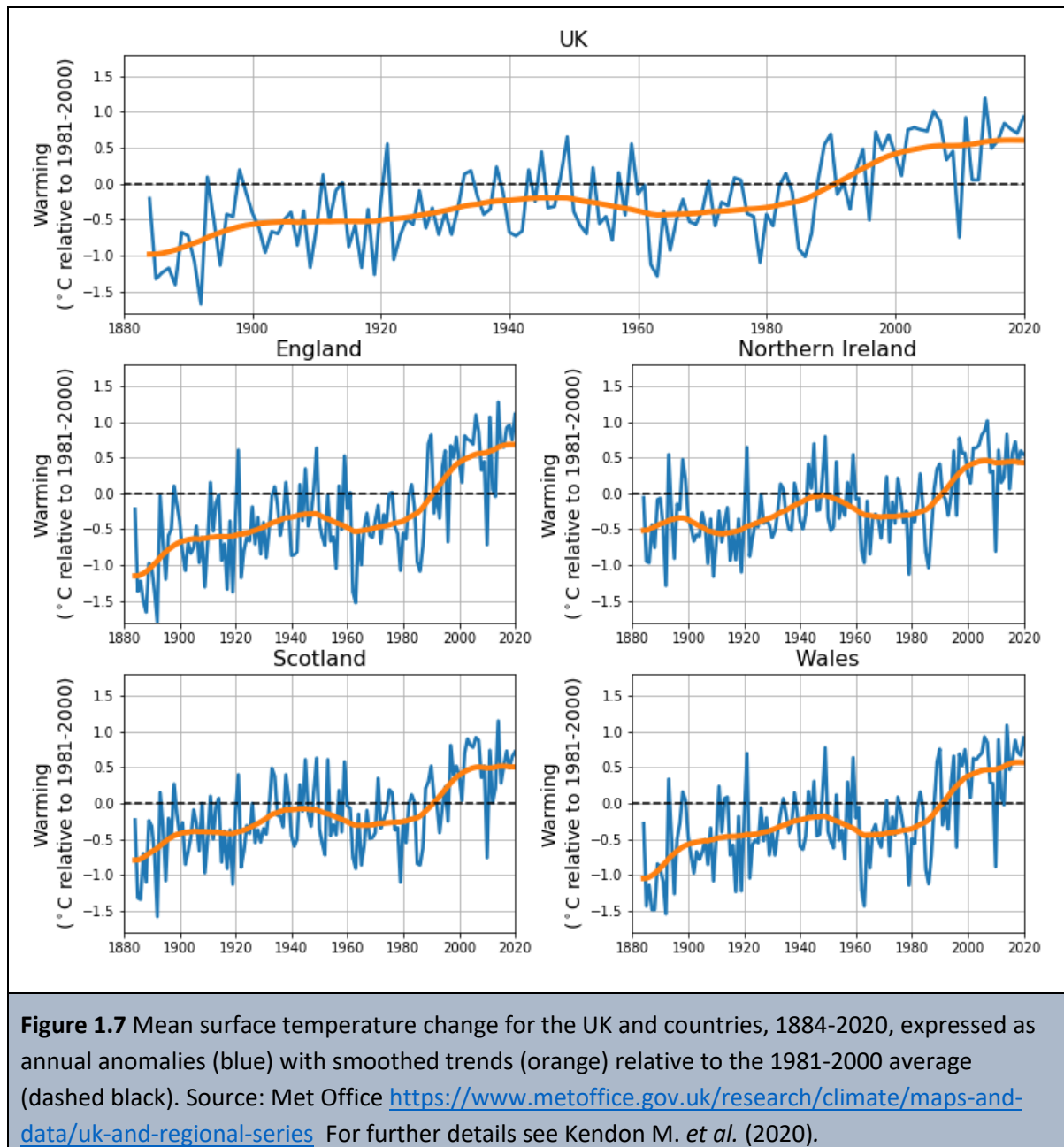
The Earth has continued to warm as measured by the GMST (Figure 1.6), with 2020 the warmest or second warmest year on record. Furthermore 2010 - 2019 concludes the warmest 'cardinal' decade globally (spanning those years ending 0-9) in records that stretch back to the mid-19th century, with the last 6 years being the warmest six years over the whole observed record. Other components of the climate system also show increasing evidence of anthropogenic warming such as declines in



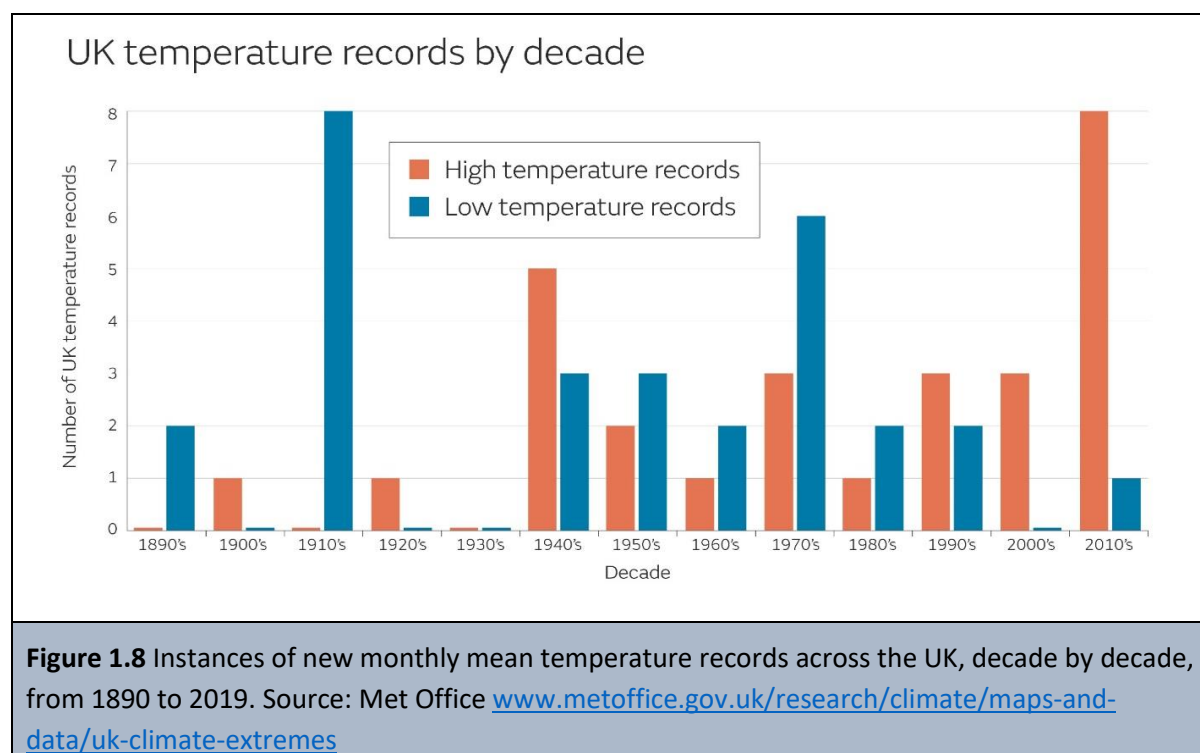
Arctic sea ice and glacier mass, rising sea levels, increases in atmospheric humidity, more warm days and fewer cold days (Blunden and Arndt, 2019).



The same evidence for continued warming is also seen in the UK land temperature record (Figure 1.7), although due to the very cold winter of 2010, the last decade has only been the second warmest of the 'cardinal' decades over the last 100 years of UK weather records, slightly behind the 2000s. Based on the Central England Temperature record (the longest instrumental temperature record in the world), the 21<sup>st</sup> century has so far been warmer overall than any 20-year period in the previous three centuries. Around the UK, coastal waters continue to warm, at rates very similar to UK land temperatures in Figure 1.7. For the most recent decade coastal waters have been 0.3°C warmer than the 1981-2010 average and 0.6°C warmer than the 1961-1990 average.



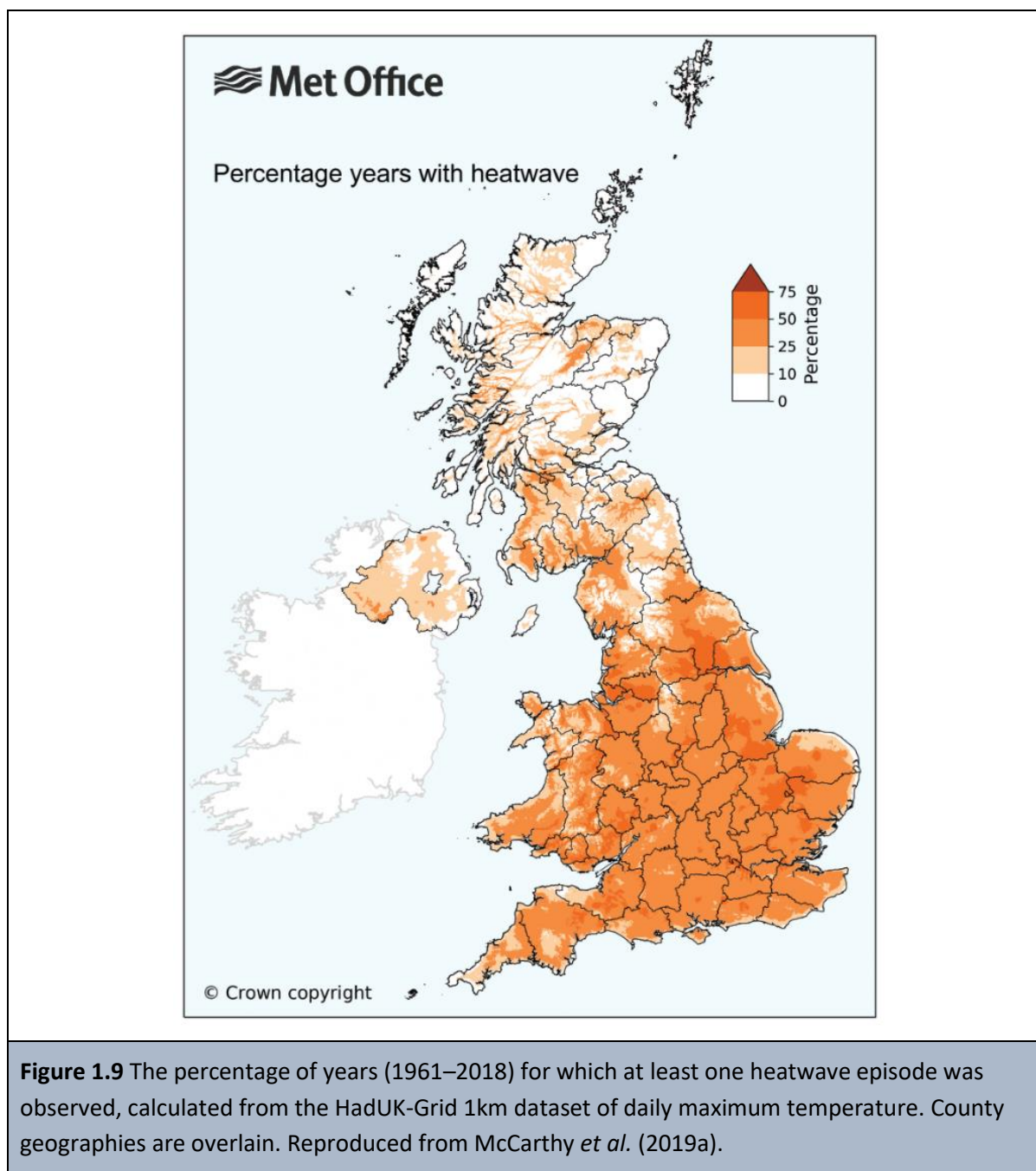
It is also notable how many of the UK's record extreme monthly temperatures have been set in the most recent decade (Figure 1.8), and how many more of them are reflecting high, rather than low, temperature extremes, again a consequence of the UK's warming climate. Furthermore, as reported by Kennedy-Asser *et al.* (2020), UK summer temperature extremes (expressed as the 95<sup>th</sup> percentile) are warming 15-48 % faster than the UK summer mean and >50 % faster than the global mean annual temperature. In July 2019, the UK recorded its highest daily maximum temperature of 38.7°C in Cambridge.



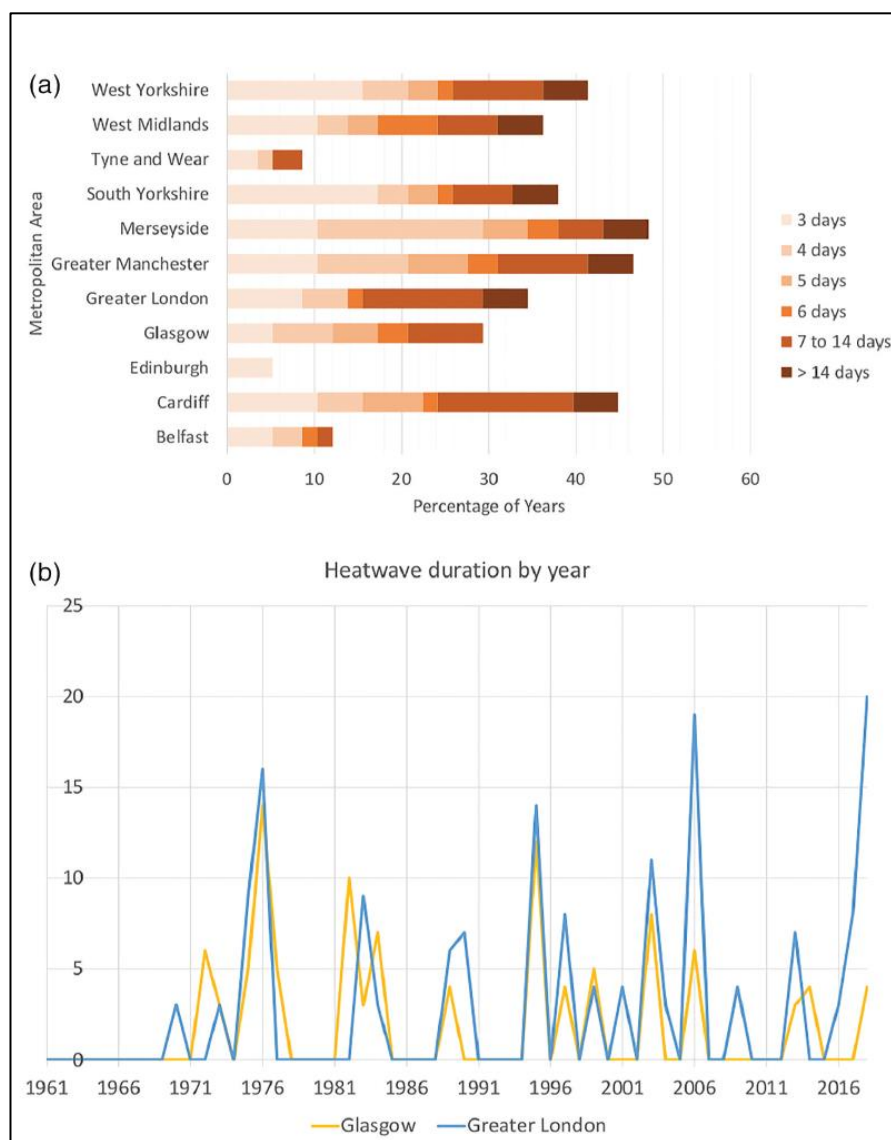
The continuing warming of the UK's climate across all seasons and nations is also reflected in other climate metrics that influence, for example, energy demand and agricultural production, including increases in the number of cooling degree days and growing degree days, and declines in the number of heating days and frost days (Kendon M. *et al.*, 2020).

A recent study of heatwaves (McCarthy *et al.*, 2019a), using the new HadUK-Grid daily dataset (Hollis *et al.*, 2019), provides important information on their spatial and temporal characteristics since 1961. In this case, a heatwave is defined using the new metric described in McCarthy *et al.* (2019a). A UK heatwave is declared when a location records a period of at least three consecutive days with maximum temperatures meeting or exceeding a heatwave temperature threshold, in which the threshold varies by UK county in the range 25–28°C.

Using this new definition, Figure 1.9 shows the frequency of heatwaves across the UK between 1961 and 2018, expressed as the percentage of years in which a heatwave is declared. Across the southern half of the UK, 30–50% of years have experienced at least one heatwave period.



The duration and frequency of individual heatwaves is shown in Figure 1.10(a) for major metropolitan areas of the UK. It shows that durations in excess of 1 week are quite common and those in excess of 2 weeks can account for around 10% of all heatwaves. Figure 1.10(b) shows the timeseries of heatwave duration for the major cities of London and Glasgow. The extreme years of 1976, 1995, 2006 and 2018 are clearly seen, along with a tendency for more heatwaves in London in recent years.



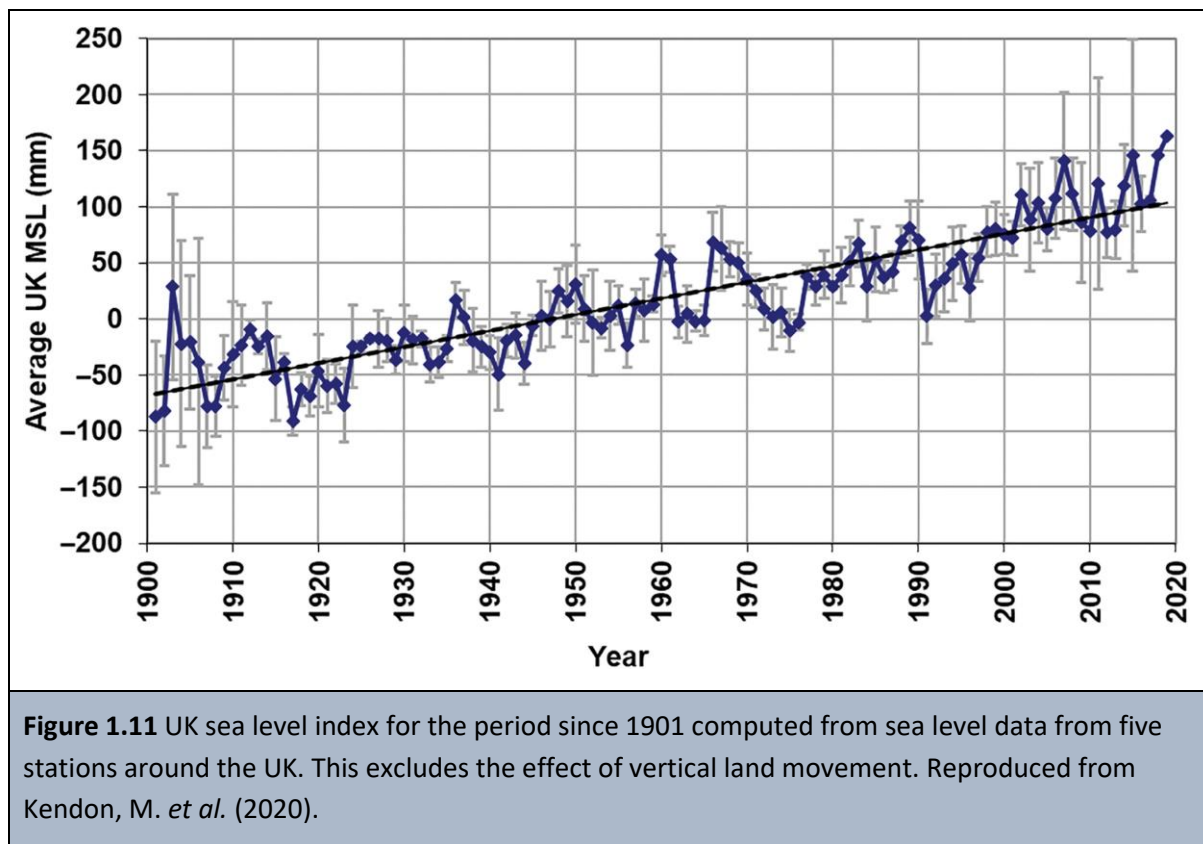
**Figure 1.10** (a) Heatwave duration presented as the proportion of years since 1961 with the listed number of heatwave days by Metropolitan Area. (b) Heatwave duration by year for Glasgow and Greater London. Reproduced from McCarthy *et al.* (2019a).

### 1.3.2 Sea Level Rise

Sea level is an important climatic impact driver for the UK, causing inundation in low-lying coastal areas, exacerbating coastal erosion, increasing tidal locking<sup>5</sup> in some rivers, and making storm surges more damaging. The latest assessments show that sea level continues to rise (Figure 1.11). Since 1901, UK sea level has risen by  $1.4 \pm 0.2\text{mm/year}$  when excluding the effect of vertical land

<sup>5</sup> Tidal locking describes the impact of tides on the ability of rivers to drain out to the sea. In very low-lying areas such as the Somerset Levels, the fall on the rivers may be so small that only during the lowest parts of the tidal cycle is the river able to drain to the sea. This was a major factor in the Somerset floods during the 2013/14 winter. This tidal locking will increase as mean sea level rises.

movement, in line with the global figure of  $1.7 \pm 0.2\text{mm/year}$ . This rise is not uniform around the coast due a number of large-scale atmosphere and ocean processes.

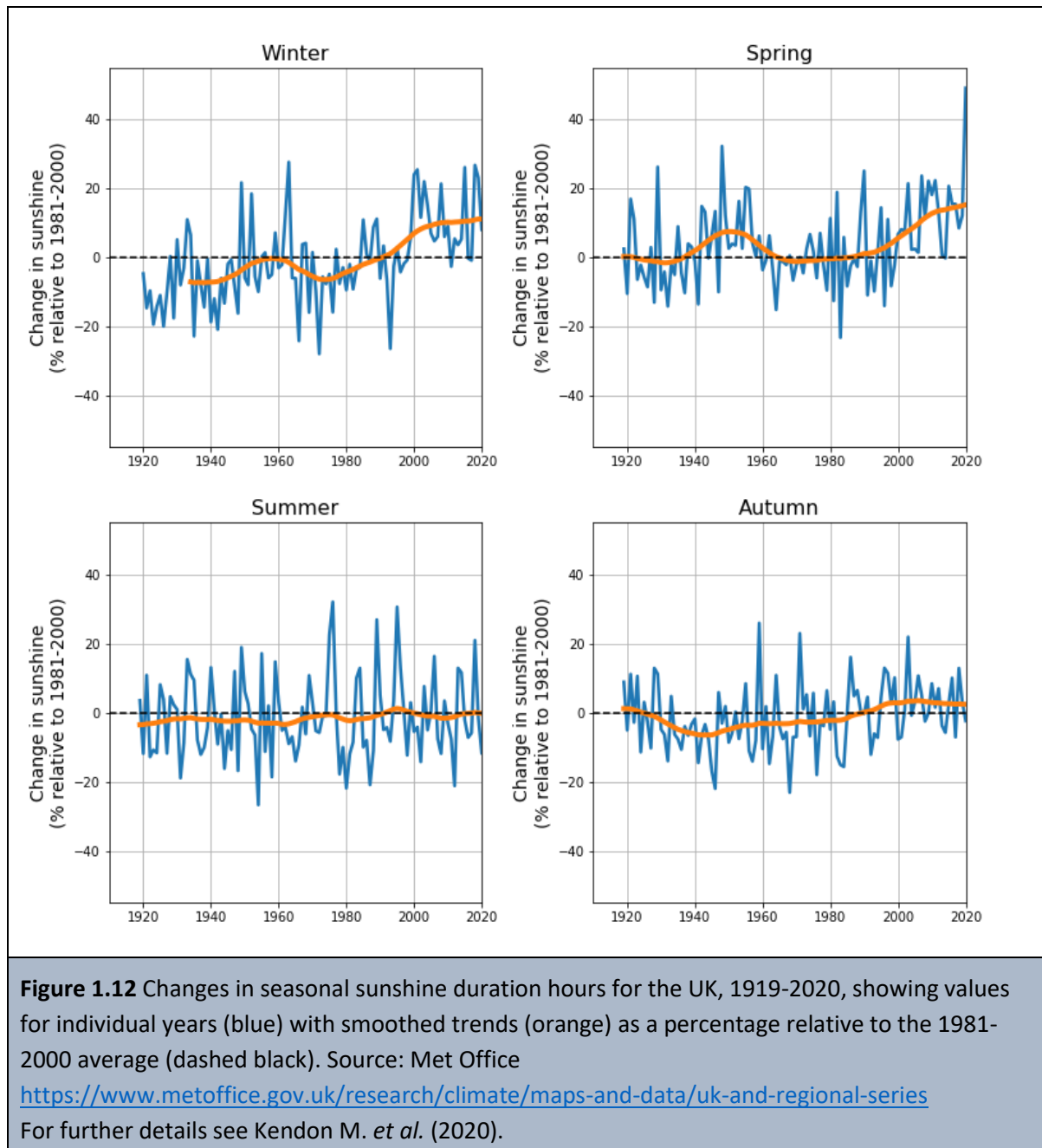


Only a limited number of stations are used to construct the long-term record. A more comprehensive reconstruction by Hogarth *et al.* (2020) for the period 1958–2018, has shown that in recent decades the mean rate of sea level rise may be higher at  $2.39 \pm 0.27 \text{ mm yr}^{-1}$  and that this rate is accelerating by  $0.058 \pm 0.030 \text{ mm yr}^{-2}$ . This is in line with the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC SROCC, 2019), which reported that the rate of rise in global mean sea level for 2006–2015 of  $3.6 \text{ mm yr}^{-1}$  is unprecedented over the last century.

### 1.3.3 Sunshine

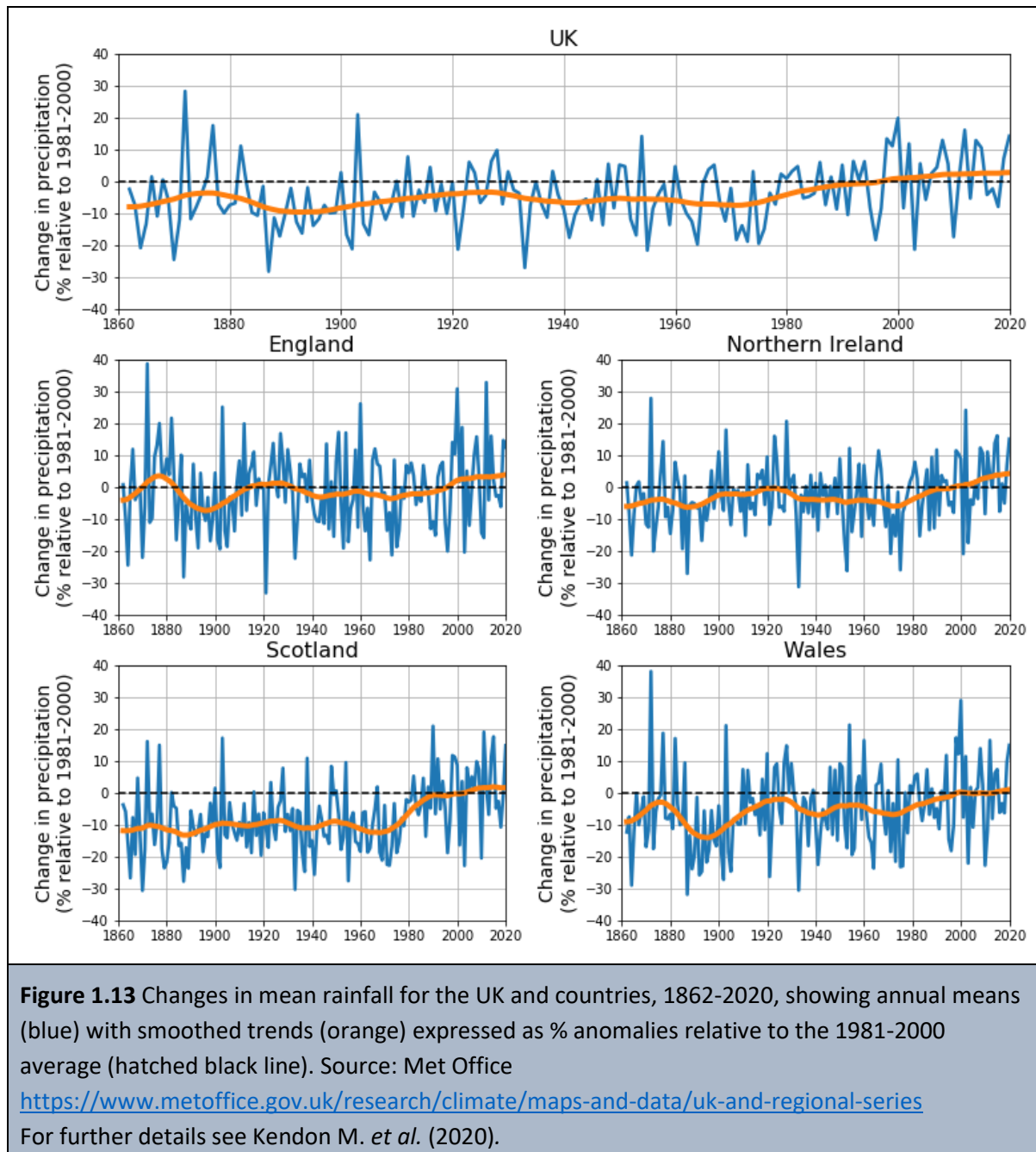
Temperature and sea level rise provide the most compelling evidence of a changing climate for the UK; changes in other weather and climate metrics are more difficult to detect due to their inherent large natural variability. However, a clear trend is emerging for increasing sunshine hours for all parts of the UK and especially during winter and spring, where the most recent decade has been higher by 11% and 16% respectively, compared with 1961–1990 (Figure 1.12). The run of sunny springs in recent years is particularly notable, with 2020 being the sunniest spring on record for all UK countries in series stretching back to 1929.





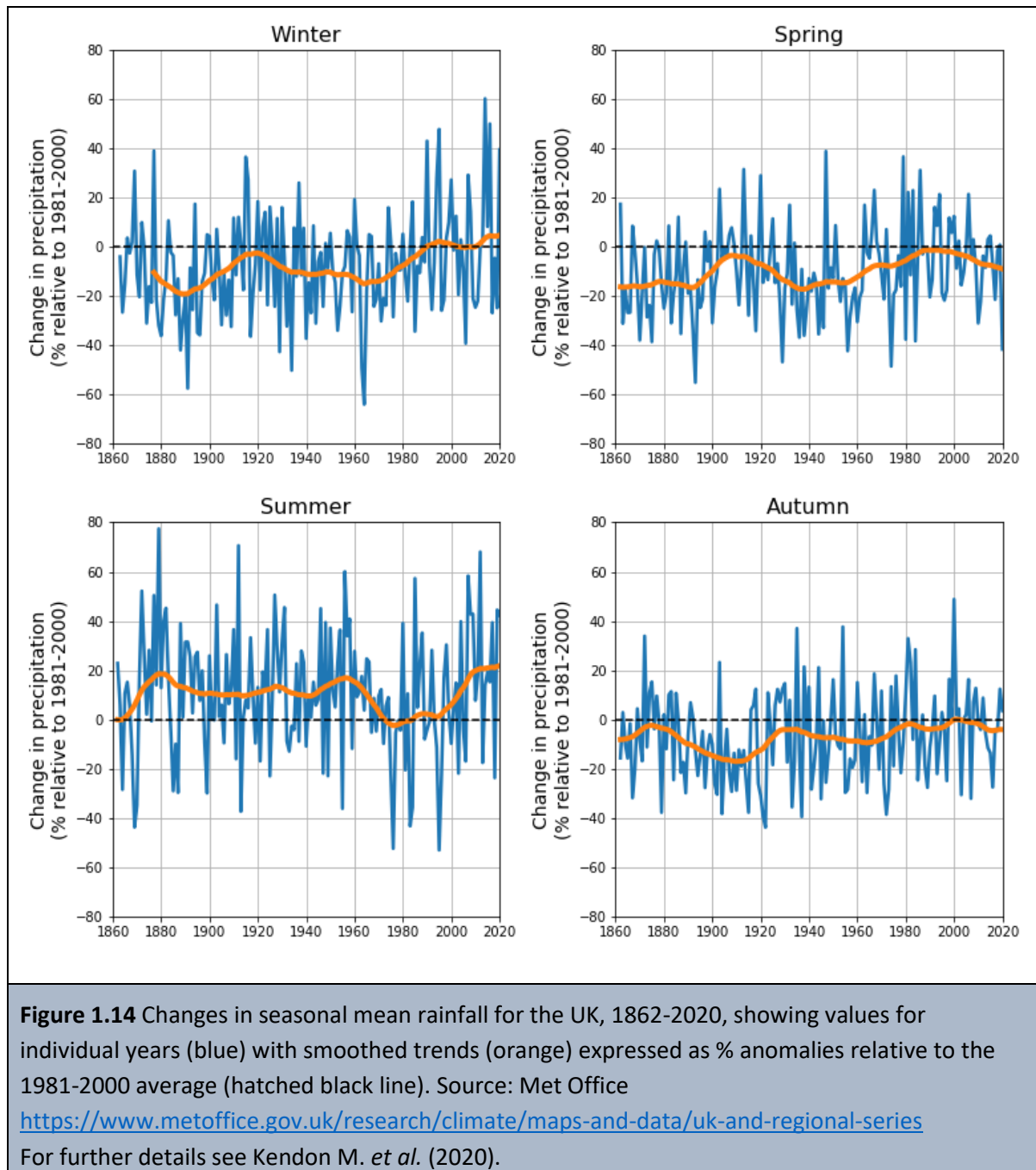
### 1.3.4 Mean Rainfall

Annual mean rainfall (Figure 1.13) is dominated by natural variations, although there are indications of small increases over the UK and its nations since the 1970s, especially for Scotland.



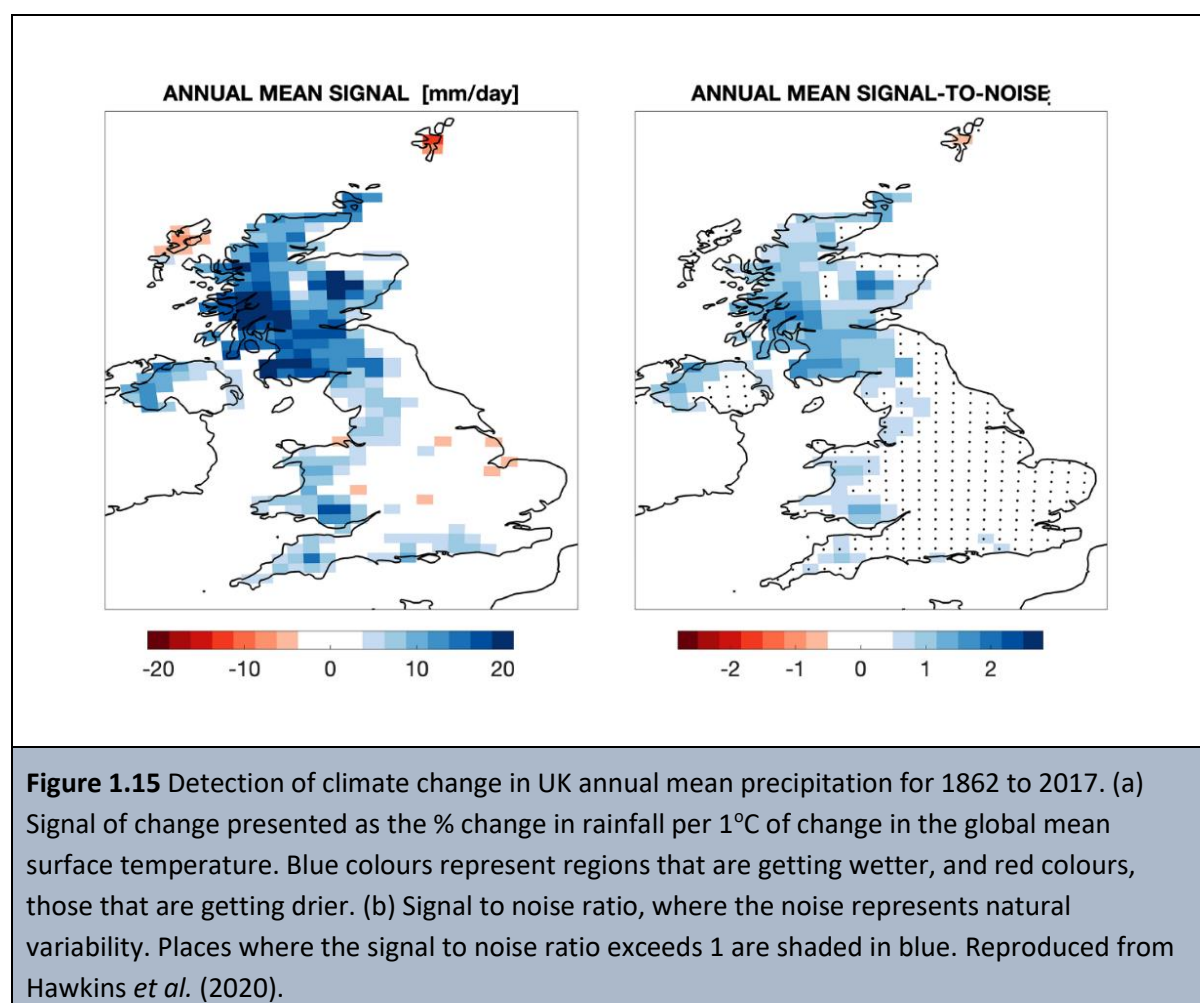
Seasonal UK rainfall has always been dominated by interannual and decadal variability (Figure 1.14). There is some evidence of increased winter rainfall in recent decades and some notable extremes (winter 2014 is the wettest winter in this series and 2016 ranked eighth wettest). Any trend towards drier summers is less evident, with a recent spell of wet summers between 2007 and 2012.





For many impacts requiring adaptation, it is the amplitude of the change relative to the local amplitude of climate variability which is more relevant. A new analysis of the UK rainfall data for 1862-2017 by Hawkins *et al.* (2020) has recently shed some light on the detection of climate change in rainfall using the HadUK-Grid dataset. By expressing the signal (S) as the % change in rainfall per 1°C change in the global mean surface temperature, they were able to detect regional variations in rainfall trends associated with global warming across the UK (Figure 1.15). When that trend is removed from the timeseries, the remaining noise (N) due to natural variability can be quantified and the ratio between signal and noise indicates if and where the effects of climate change are beginning to emerge from natural variability.

Figure 1.15(a) shows that the signal (S) for trends in annual mean rainfall associated with global warming is dominated by increases, mainly over the west side of the UK and especially over Scotland. Hawkins *et al.* (2020) further showed where the signal exceeded the noise (S/N), identifying Scotland and the mountainous regions of western England (Figure 1.15(b)). Where S/N exceeds 1, this can be interpreted as places where the climate is now moving from the ‘familiar’ towards being ‘unusual’, relative to lived experience, using the terminology as defined by Frame *et al.* (2017).



In all regions, the influence of climate change is to increase rainfall, consistent with fundamental physics that says that warmer air holds more moisture (i.e., for 1°C rise in temperature, atmospheric moisture content – and by inference regional rainfall - increases by 7%). Figure 1.15(b) clearly identifies Scotland and the mountainous regions of western England where S/N exceeds 1 and therefore where the influence of climate change is already emerging and potentially challenging our resilience.

### 1.3.5 Rainfall extremes

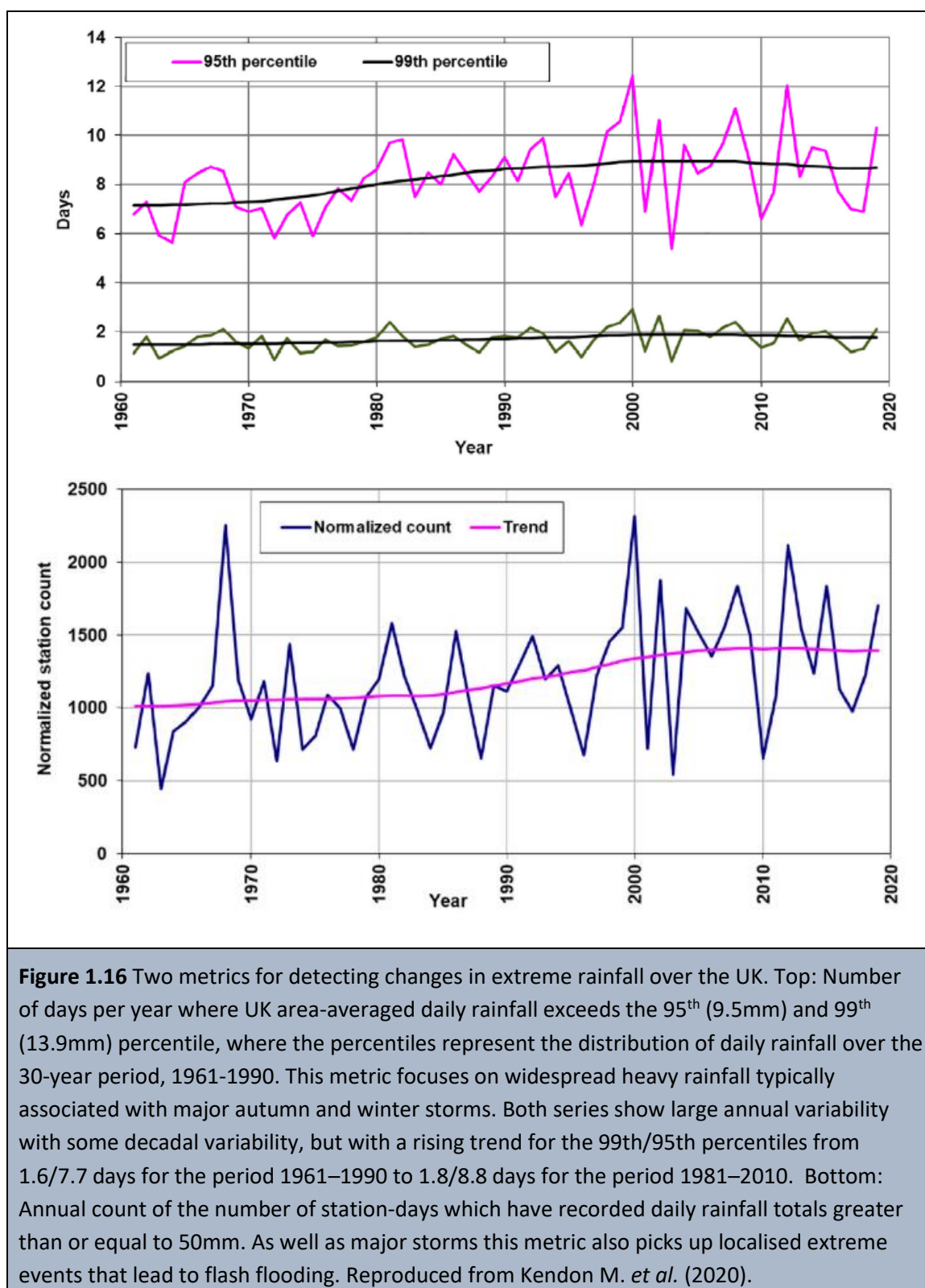
While robust evidence for trends in the UK's annual and seasonal rainfall is emerging year on year, we need also to consider whether the same is true for extreme rainfall which can be particularly damaging.

There is a growing body of literature (e.g., Guerreiro *et al.*, 2018) which argues that the effects of global warming on the hydrological cycle are being manifested in changes in the frequency and intensity distributions of daily and sub-daily rainfall, even when averages over longer timescales are stable.

There is some evidence for the increasing occurrence of widespread heavy daily rainfall across the UK in the last few decades (Figure 1.16), such as autumn 2000 and winter 2013/14. Although the record is too short to be conclusive, this is in line with fundamental physics that says that warmer air holds more moisture. In other words, a weather system today would give more rainfall than the same system in 1950. The statistics on local extreme daily rainfall (Figure 1.16), based on individual station records, also suggest an increasing occurrence, although the gauge network is not ideally suited to detect localized events.

In a major review of the latest evidence on the current anthropogenic intensification of short-duration rainfall extremes, Fowler *et al.* (2020) conclude that:

- Heavy rainfall extremes are intensifying with warming at a rate generally consistent with the increase in atmospheric moisture (i.e., 7% per °C), for accumulation periods from hours to days.
- In some regions, stronger increases in short-duration, sub-daily, extreme rainfall intensities have been identified, up to twice what would be expected from atmospheric moisture increases alone.
- Stronger local increases in short-duration extreme rainfall intensities are related to convective cloud feedbacks involving local storm dynamics.
- The evidence is unclear whether storm size has increased or decreased with warming; however, increases in rainfall intensity and the spatial footprint of the storm can compound to give significant increases in the total rainfall during an event.
- Evidence is emerging that sub-daily rainfall intensification is related to an intensification of local flash flooding. This will have serious implications for flood risk management and requires urgent climate-change adaptation measures.



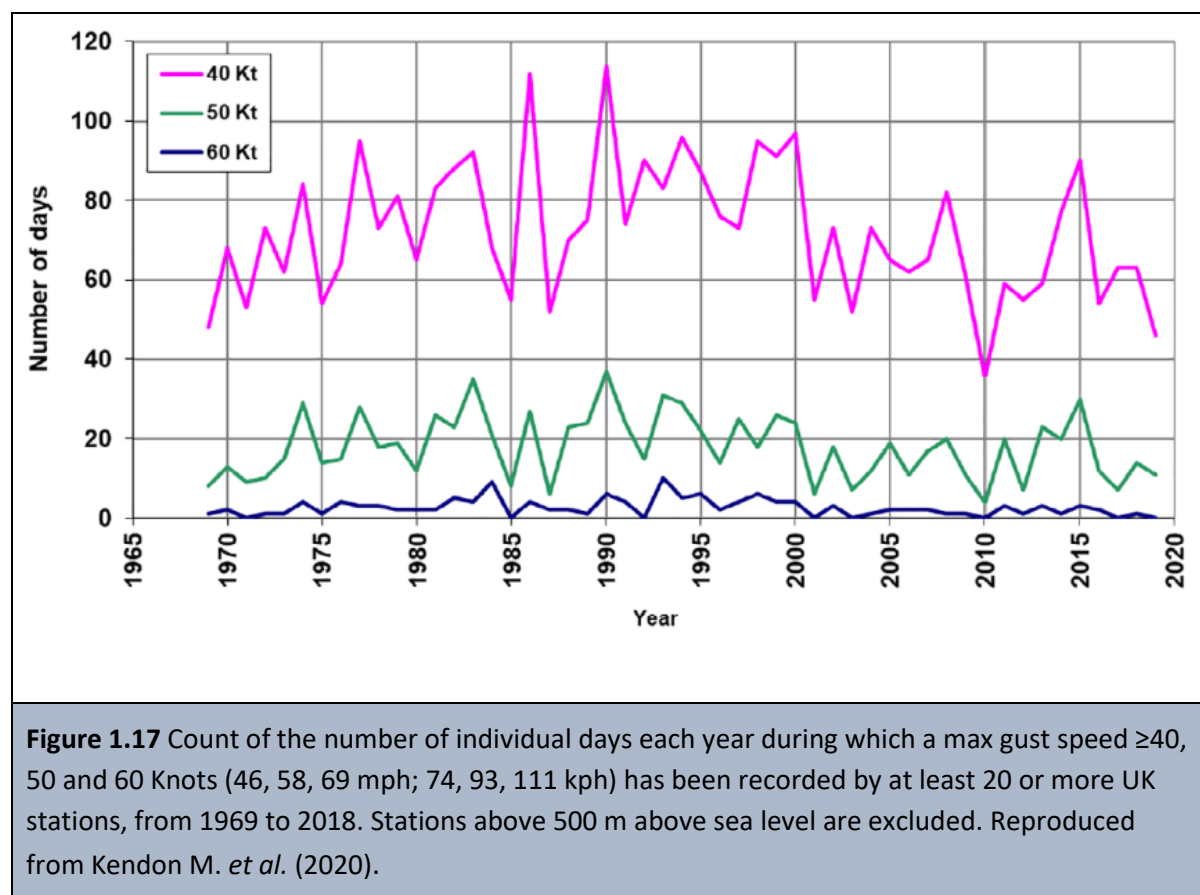
### 1.3.6 Storminess and winds

Storms are an important climatic impact driver for the UK and there has been considerable debate on whether storminess is increasing, particularly after the 2013/14 winter, which was the stormiest

winter for at least 143 years when cyclone frequency and intensity are considered together (Matthews *et al.* 2014).

A comprehensive review of the evidence has been presented by Feser *et al.* (2015) who concluded that there is as yet no clear evidence for increased storminess. This was confirmed by a more recent study by Krueger *et al.* (2019). Both studies showed that trends in storm activity depend critically on the time period analysed, and that the apparent increase in storminess between 1960 and 1990 is actually part of a longer-term record that reveals multi-decadal variability. In other words, large-scale natural climate variability, such as the North Atlantic Oscillation, dominates the intensity and frequency of UK storms.

Kendon M. *et al.* (2020) confirmed this result when they analysed strong wind gusts across the UK (Figure 1.17), which showed increases in wind gusts over 40 knots in the latter part of the 20<sup>th</sup> century and a decline thereafter. Nevertheless, more research is needed to address this important question for the UK, since major storms can cause widespread damage, from flooding, winds and waves to coastal storm surges.



### 1.3.7 Summary

The latest observations show that the UK continues to warm, sea levels continue to rise, and an increasing number of climatic impact drivers are beginning to show clearer evidence of a changing

climate. Beyond the mean climate there is a growing body of evidence for changes in the frequency and/or intensity of high-impact weather events, such as extreme daily rainfall and heatwaves. New records are being set more frequently, with the UK experiencing unprecedented high temperatures and heavy rainfall. However, the evidence base for changes in storminess is weak and this needs to be addressed with some urgency. The next section will provide the latest evidence on how to interpret these events and the extent to which they can be attributed to climate change.

## 1.4 Interpreting the observational evidence on extremes

The previous section has identified a number of climatic impact drivers where climate change can be detected, in other words the observations lie outside the envelope of natural variability. The next question is whether those changes can be attributed to anthropogenic forcing or whether they are due to other drivers such as multi-decadal variability. We are now confident that the trends in UK average surface temperature can be attributed to anthropogenic global warming, but other climatic impact drivers, especially related to precipitation are still challenging.

We know that extreme weather and climate events can be very costly, and it is increasingly important to know whether human influences are affecting their severity and frequency so that we can plan accordingly. Knowing the relative contribution of climate change to these events allows us to assess how our risk envelope is changing and what our near-term adaptive responses should be.

Since CCRA2, the science of extreme event attribution has continued to develop (e.g., Stott *et al.*, 2016, Vautard *et al.*, 2019), including progress towards an operational attribution service (e.g., <https://www.worldweatherattribution.org>). There are two possible approaches to attribution of extremes. The first is framed around the probabilities of such an event occurring in a world with and without raised concentrations of greenhouse gases due to human activity. It relies on model simulations and is therefore dependent on the skill of the model in capturing these extreme events (e.g., Stott *et al.*, 2004). The second approach is framed around a storyline, which examines the role of the various factors contributing to a specific event as it unfolded, including the anomalous aspects of the meteorology. By analyzing the contribution of the particular weather pattern to the event, it is possible to isolate the potential contribution from climate change.

A good example of these two approaches is seen in the recent analysis of the causes of the UK summer 2018 heatwave (McCarthy *et al.*, 2019b). Based on the probabilistic approach using an ensemble of global climate simulations, they concluded that climate change had increased the likelihood of the summer 2018 heatwave by a factor of 30, assuming of course that the simulations are able to represent the weather patterns that give rise to UK heatwaves with some fidelity.

However, these estimates do not include the specific context of each heatwave and we know that each one is set up differently and framing the question around an event-based storyline approach, enables this to be addressed. McCarthy *et al.* (2019b) showed that most of the high temperature anomalies during the summer 2018 heatwave can be explained by the prevailing circulation anomalies - in particular, a strongly positive summer NAO that raised the sea surface temperatures of UK coastal waters, as well as by other feedbacks, such as the extremely low levels of soil moisture following an extended dry spell during early summer. Importantly, though, McCarthy *et al.* also note that these factors alone are not sufficient to explain the intensity of the heatwave, which also has an underlying cause related to the warming UK climate.

This study emphasises the importance of understanding whether the specific circulation patterns that give rise to extreme events will become more prevalent or not under climate change. Other studies of recent extremes have shown, for example, that the extremely cold start to the spring of 2018 is much less likely under global warming, although the circulation pattern that gave rise to it may be slightly more likely (Christidis and Stott, 2020).

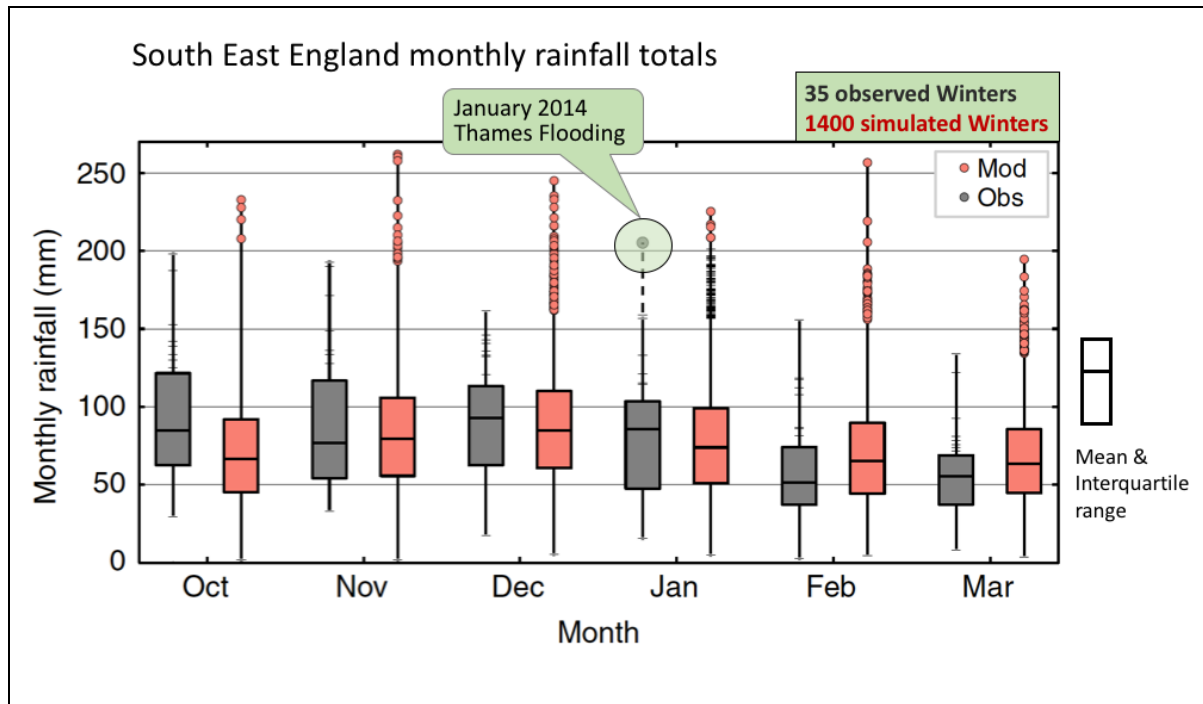
The Doncaster Floods of Autumn 2019 have yet to be formally attributed to climate change. The summer and autumn were exceptionally wet and with the jet stream positioned anomalously to the south in October, a series of cyclonic systems brought prolonged and persistent rainfall on top of already saturated soils. Likewise, the severe Welsh and Severn floods of February 2020 were preceded by a very wet winter, with the compounding effects of a series of storms, none of which were exceptional. As with the widespread flooding that occurred in 2013/14 and again in 2015/16, the prevailing weather patterns clearly played the key role (e.g., Christidis and Stott, 2015). Nevertheless, the extreme rainfall totals and the severity of the flooding are consistent with the basic premise that a warming world holds more moisture; in other words, the same weather system 50 years ago would have produced less rainfall than today.

One of the issues in understanding extremes for the recent past and present day is that the observational record does not necessarily capture the full range of possible outcomes for extreme weather in a particular location, even under the current climate, simply because such events are by definition rare. For the UK, this is particularly challenging. The natural volatility of our weather means that the observational record is far too short to characterise extreme events with confidence and provide robust estimates of return periods. At the same time the statistics of observational extremes are non-stationary (i.e., they vary with time) due to low frequency, multi-decadal natural variability and the emerging effects of anthropogenic climate change. Empirical methods for analysing extremes based on the limited observational record, tend to assume stationarity and potentially have limitations.

Since CCRA2, weather and climate models have been increasing in the level of skill and granularity. They are now able to provide exciting opportunities to use model simulations to produce large sets of synthetic but meteorologically plausible extreme weather events (orders of magnitude larger than observational records) for the current (and future) climate; in other words, pseudo-observations that act to fill out the extreme ends of the observed distribution. They enable return periods (e.g., 1 in 100 years) to be estimated more robustly than using empirical methods based on the short observational record, provided of course that it can be shown that the model can represent, statistically, the real world (Thompson *et al.*, 2017). Consequently, they may serve to provide an improved baseline understanding of current likelihood of extreme weather events, which is valuable in and for itself; it informs planning today, strengthening resilience, as well as providing a reference against which to assess future changes. Synthetic event sets can also be used to explore correlated extremes (such as simultaneous bread-basket crop failures e.g., Kent *et al.*, 2017) and clustering of extremes (such as European windstorms e.g., Priestley *et al.*, 2018).

This methodology, known as UNSEEN (UNprecedented Simulation of Extremes with Ensembles) was first introduced in the Government's National Flood Resilience Review (2016) following the severe flooding during the 2015/16 winter and published by Thompson *et al.* (2017). Figure 1.18 gives an example of the simulated and observed events sets for monthly precipitation in South East England; it shows that by sampling many more meteorologically plausible conditions, a large number of

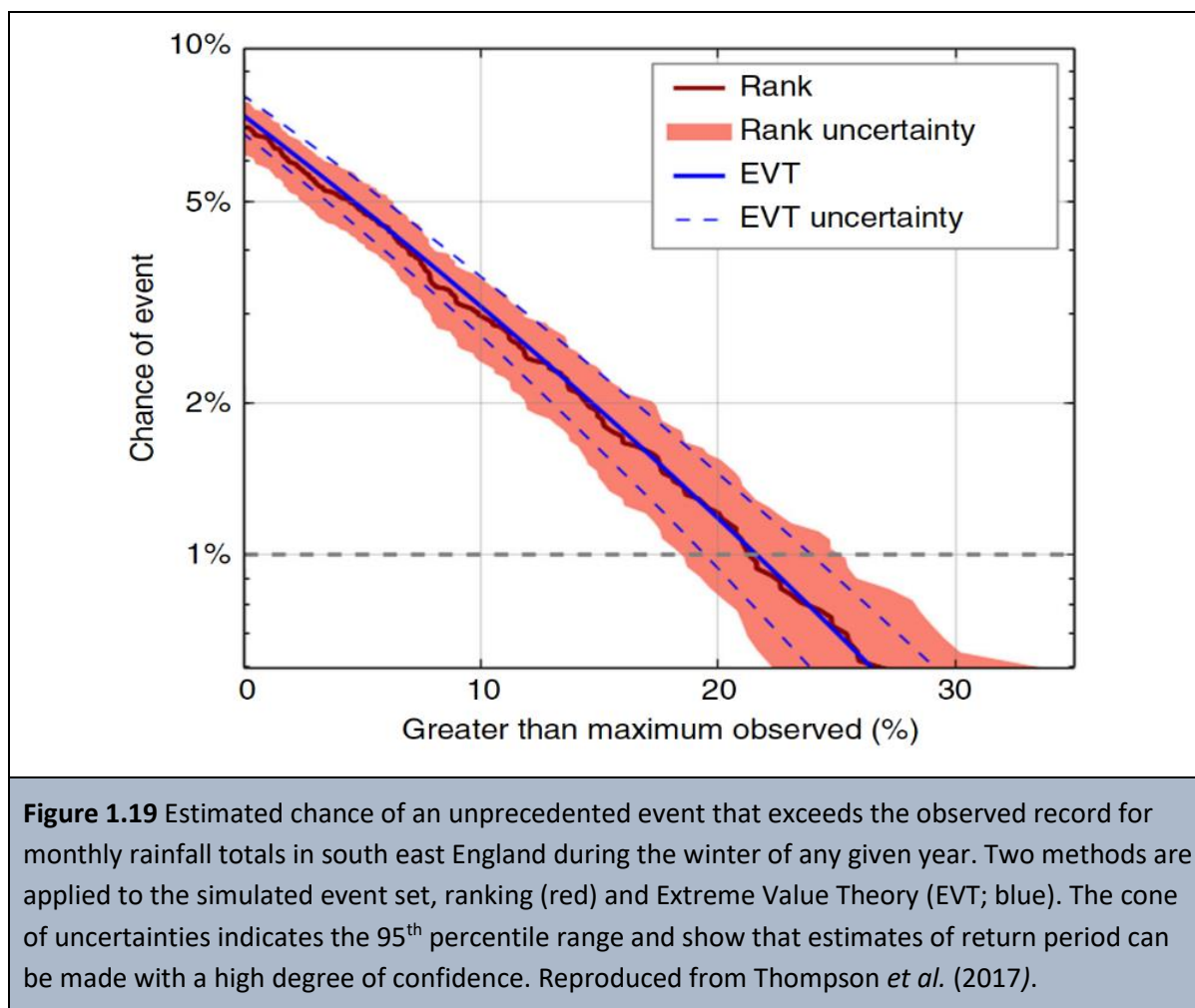
unprecedented extremes can be identified, due to the natural volatility of weather systems. For example, it suggests that the severity of flooding of the Thames in 2014 should not be unexpected, even under present climate conditions, with even more extreme monthly rainfall totals possible.



**Figure 1.18** Example of a climate model-generated, synthetic event set for monthly rainfall for the current climate (red) versus observations (grey), showing that by sampling many more meteorologically plausible conditions, a large number of unprecedented extremes can be found given by the red circles. The median and spread of the simulated and observed events is shown by the box and whisker plots which demonstrate that the simulation event set does not differ statistically from the observations. Reproduced from Thompson *et al.* (2017)

The size of these simulated event sets is many times larger than observations alone and allows exceedance probabilities to be calculated with much more confidence. For example, it can be concluded from Figure 1.19 that currently, in any year, there is a 10% chance of an unprecedented month's rainfall, and that furthermore, there is a 1% risk of receiving 20-30% more rainfall than ever observed before, just from natural variability within today's climate.





The UNSEEN methodology has also been applied to other extremes, such as UK summer heat waves. McCarthy *et al.* (2019b) considered the 2018 event in which summer average temperatures were close to +2°C above the 1981–2010 average for a large swathe of southern and central England and Wales. Using a simulated event set of 4720 samples, McCarthy *et al.* (2019b) showed that there is an 11% chance in any current year of summer temperatures exceeding those in 2018, and a 1% chance that temperatures anomalies may exceed 1°C or more above the 2018 values.

UNSEEN complements future projections from UKCP18 by providing a valuable new tool for assessing current and near-term climate risks by providing better estimates of the tails of the observed distribution for the current climate and providing bounds on what is meteorologically plausible in terms of extreme events. However, like the attribution studies documented above, UNSEEN relies on the model’s ability to represent accurately the statistics of the real world as far as that is possible from the limited observational record, and so detailed evaluation of the model is an essential first step.

In summary, it is now possible to attribute some changes in UK weather extremes to climate change, and significant progress has continued to be made in the attribution of extreme weather events since CCRA2. The science remains challenging because of the UK’s highly variable weather and the fact that these events are, by definition, rare. New research has emphasised the importance of understanding the meteorological context of each individual event, such as the prevailing weather

patterns and the antecedent conditions, as well as recognising that unprecedented extremes will continue to occur just because of natural variability. It remains the case that recent extremes can be largely explained by the prevailing atmospheric circulation anomalies; however, these circulation changes alone are not necessarily sufficient to explain the intensity of the event, which may also have an underlying contribution from the warming UK climate.

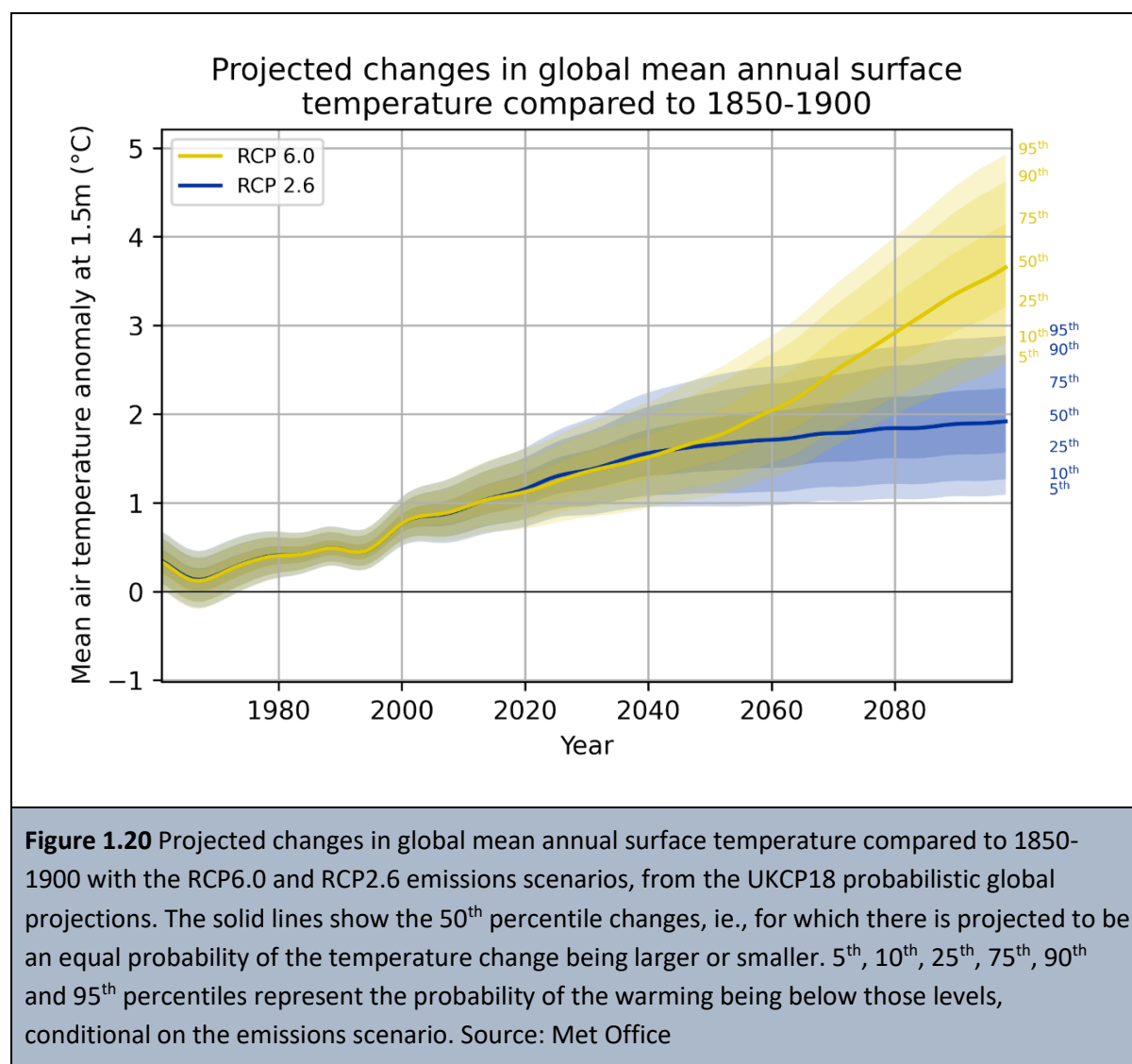
## 1.5 Future Climate Change

This Section draws on the latest UK Climate Projections – UKCP18 – which provide the most up-to-date and comprehensive assessment of future climatic impact drivers for the UK, along with projections of global climate change consistent with the UK projections. It will highlight key differences from the evidence base used in CCRA2 where appropriate. Studies using other climate projections were also used in CCRA3, in addition to information based on UKCP18 – further details on the integration of information from different sources are given in Chapter 2.

### 1.5.1 Projected future global warming

Future changes in global average temperature will depend on future human-caused emissions of greenhouse gases and on the response of the global climate system to these emissions (see Chapter 0). Any particular pathway of future global warming could therefore arise from a number of different combinations of future emissions and climate system responses.

UKCP18 provides global probabilistic projections of the percentage likelihood of different levels of global average temperature change resulting from four emissions scenarios. Two of these – the RCP2.6 and RCP6.0 emissions scenarios – are broadly representative of the pathways to approximately 2°C and 4°C above preindustrial levels by 2100, as used here in CCRA3 to frame the risk assessment (see Introduction Chapter: Betts and Brown, 2021). As Figure 1.20 shows, with the RCP6.0 emissions scenario, the projections give approximately a 30% probability of global warming exceeding 4°C, relative to 1850-1900 (an approximation of the climatic conditions of preindustrial levels) by 2100; with the RCP2.6 emissions scenario, there is slightly more than a 50% probability of global warming at 2100 being below 2°C, relative to 1850-1900. These probabilities reflect uncertainties in both transient climate response and the strength of carbon cycle feedbacks. Importantly, the probabilistic projections are not based on the high-sensitivity model HadGEM3 - they are built from perturbed-parameter ensembles of the HadCM3 model (as used in UKCP09), and also include information from the CMIP5 multi-model ensemble.



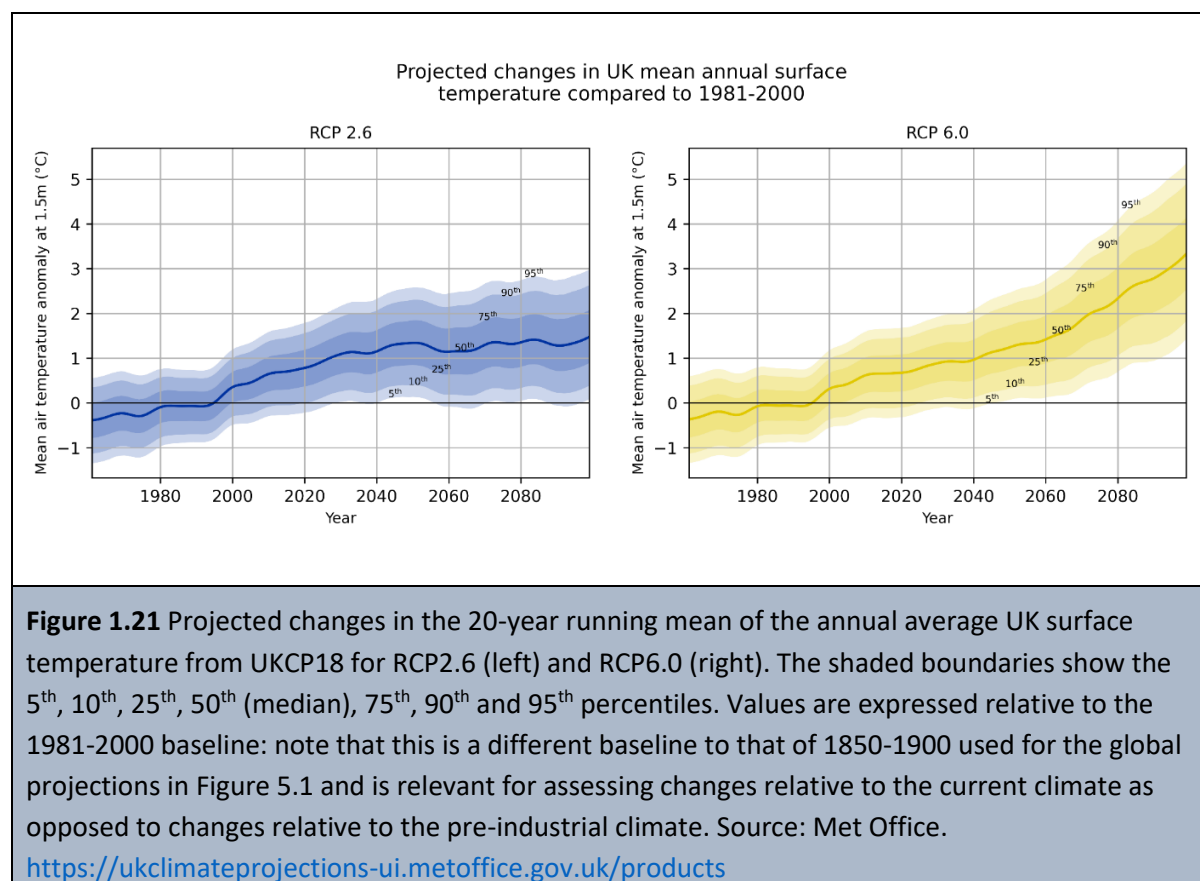
UKCP18 also includes projections with the high-end RCP8.5 scenario, especially for the regional and local projections (see Section 1.2.1). Some of these simulations project warming below the 95<sup>th</sup> percentile of that projected with the RCP6.0 emissions scenario, but most are above that. UKCP18 further includes projections with the RCP4.5 emissions scenario; this gives warming that overlaps the lower and upper parts of the ranges with RCP6.0 and RCP2.6 emissions respectively. Further information on this, and comparison with other global warming projections including those used in the UKCP09 projections, and the CMIP5 projections used in the IPCC 5<sup>th</sup> Assessment Report, is given in Annex 1.

### 1.5.2 Projected changes in the UK's annual and seasonal average climate

UK climate change depends on emissions scenarios and global-scale climate responses, and also on the nature of regional climate responses to the global-scale forcing. Overall, the UK is projected to experience ongoing increases in temperature until the middle of the 21<sup>st</sup> Century under all scenarios examined by UKCP18, including RCP2.6. Until that point, the magnitude of regional climate change

depends more on the regional climate responses to a given amount of global average warming, than the difference between the emissions scenarios (Figure 1.21).

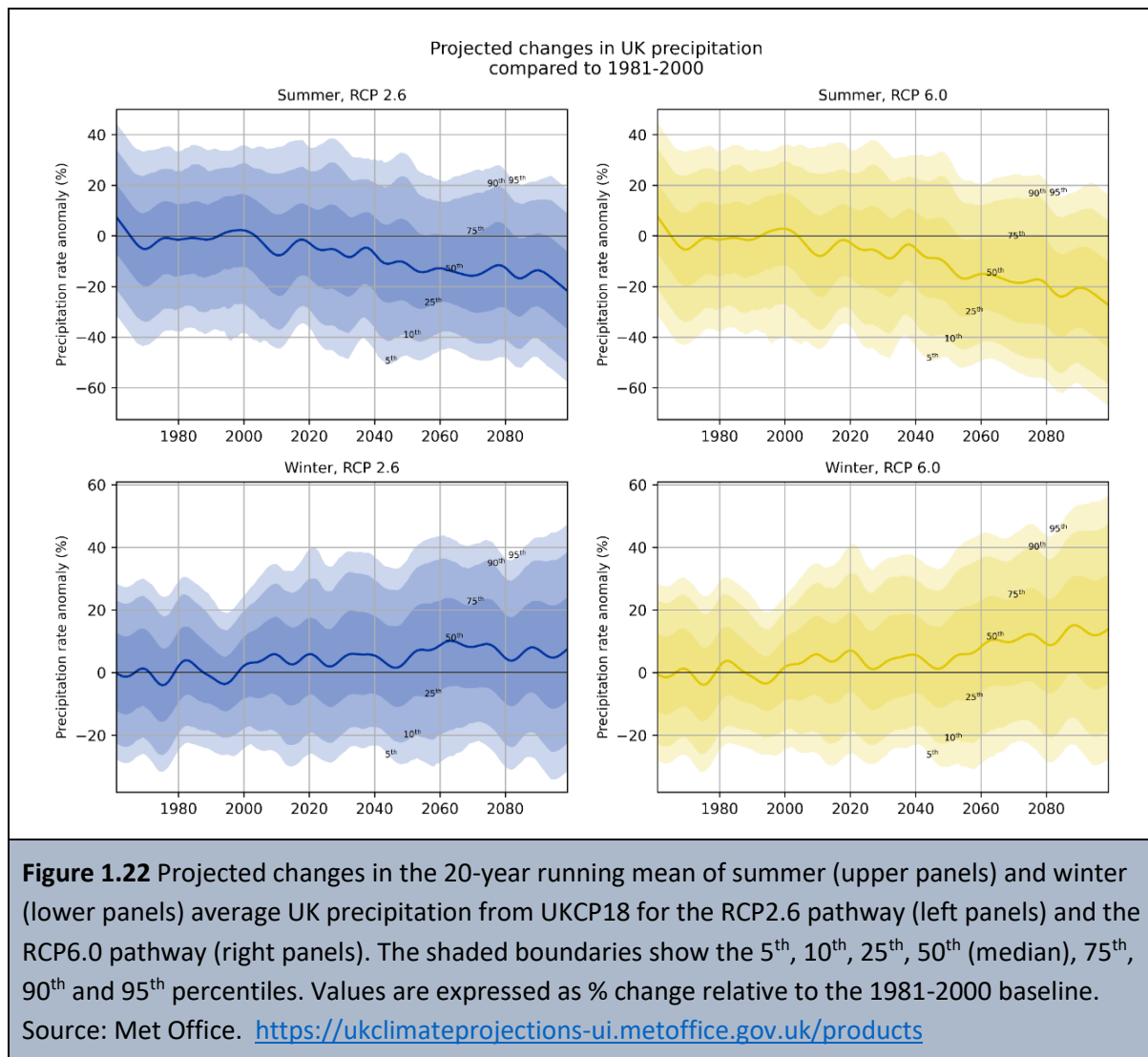
Beyond mid-century, the magnitude of UK climate change depends on the path of future emissions as well as on the regional and global climate response (Figure 1.21). The spread in the projected temperatures by 2100 is larger for RCP6.0 than RCP2.6 and reflects, in part, the increasing contribution to uncertainty from carbon cycle feedbacks, which come into play more substantially in the latter half of the century and at higher temperatures. The warming experienced in the UK is projected to be greater in the summer than the winter (Murphy et al., 2018).



As in earlier assessments there are significant differences in the precipitation signal between winter and summer (Figure 1.22). Even for the RCP2.6 pathway, winters are projected to become wetter overall, whereas summers are expected to become drier. The spread of probabilities is broader in summer than winter, although the difference between the two scenarios is small throughout the century.

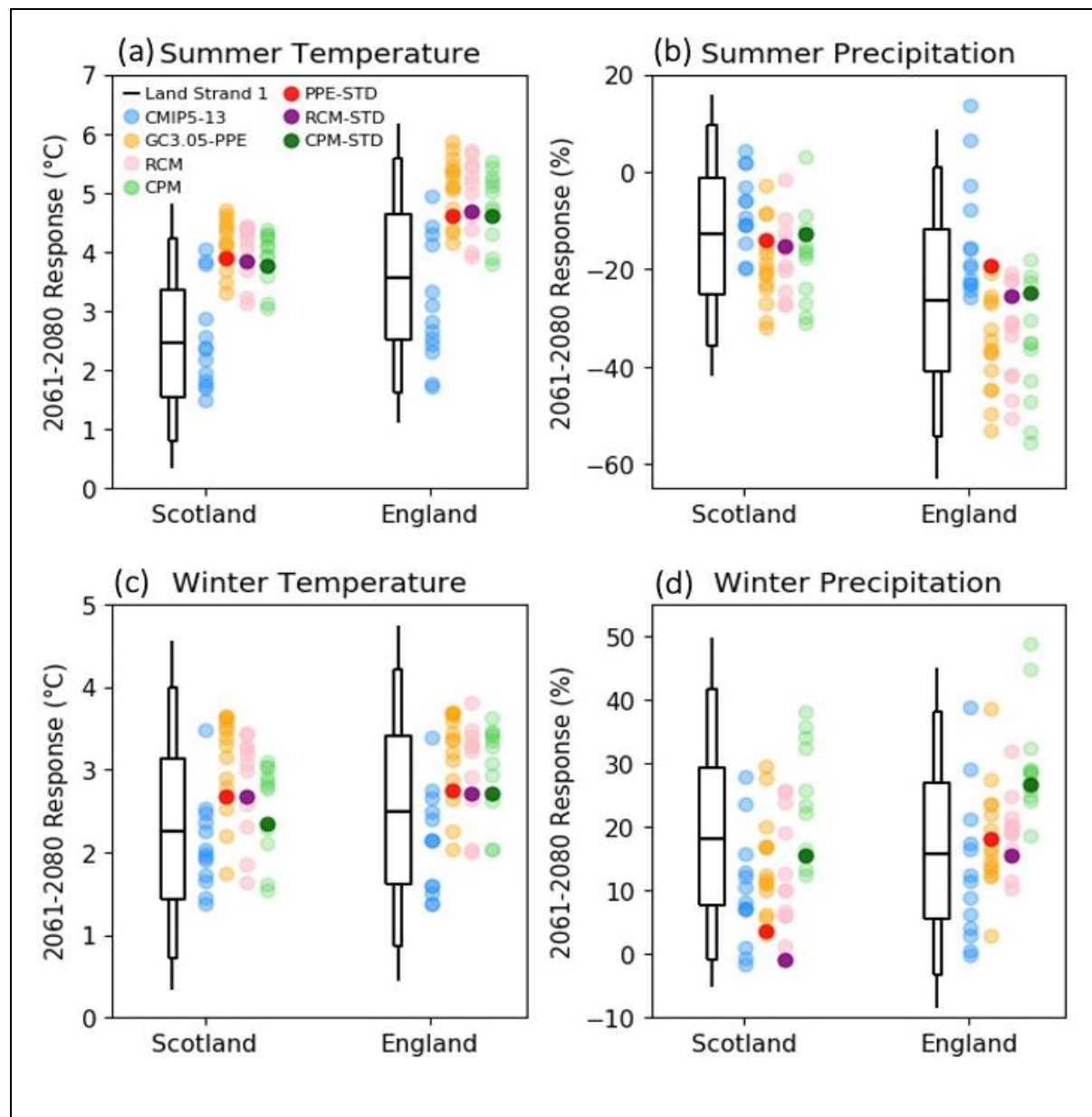
A key point is that while drier summers are generally more likely across the UK, wetter summers are also possible – for most of the country there is a 10% probability of 20-year average summer precipitation increasing by at least 10%. Drier summers are therefore far from certain in the near term. For winter, however, the lower part of the likelihood range remains constant; at any time in the projections, it is about 10% likely that the 20-year mean precipitation would be more than 20%

below that for 1981-2000. So, there is no projected change in the likelihood of dry winter conditions when considering the 20-year mean.



A key question is how the HadGEM3-based projections compare with the UKCP18 probabilistic projections for temperature and precipitation shown in Figures 1.21 and 1.22. A comparison of the projections for 2061-2080 is shown in Figure 1.23. Here the RCP8.5 scenario is used because the projections with HadGEM3 and its related regional simulations were only performed for this pathway.

The new probabilistic projections are given by the black box and whisker diagrams; these include CMIP5 (blue dots) and the new ensemble of HadGEM3 (orange dots). Both CMIP5 and HadGEM3 were used to construct the CCRA3 probabilistic projections. The new 12km regional climate model (RCM) and 2.2km convective permitting model results are shown in the pink and green dots respectively; they are both driven by boundary conditions from the HadGEM3 ensemble (see Annex 1 for more details).



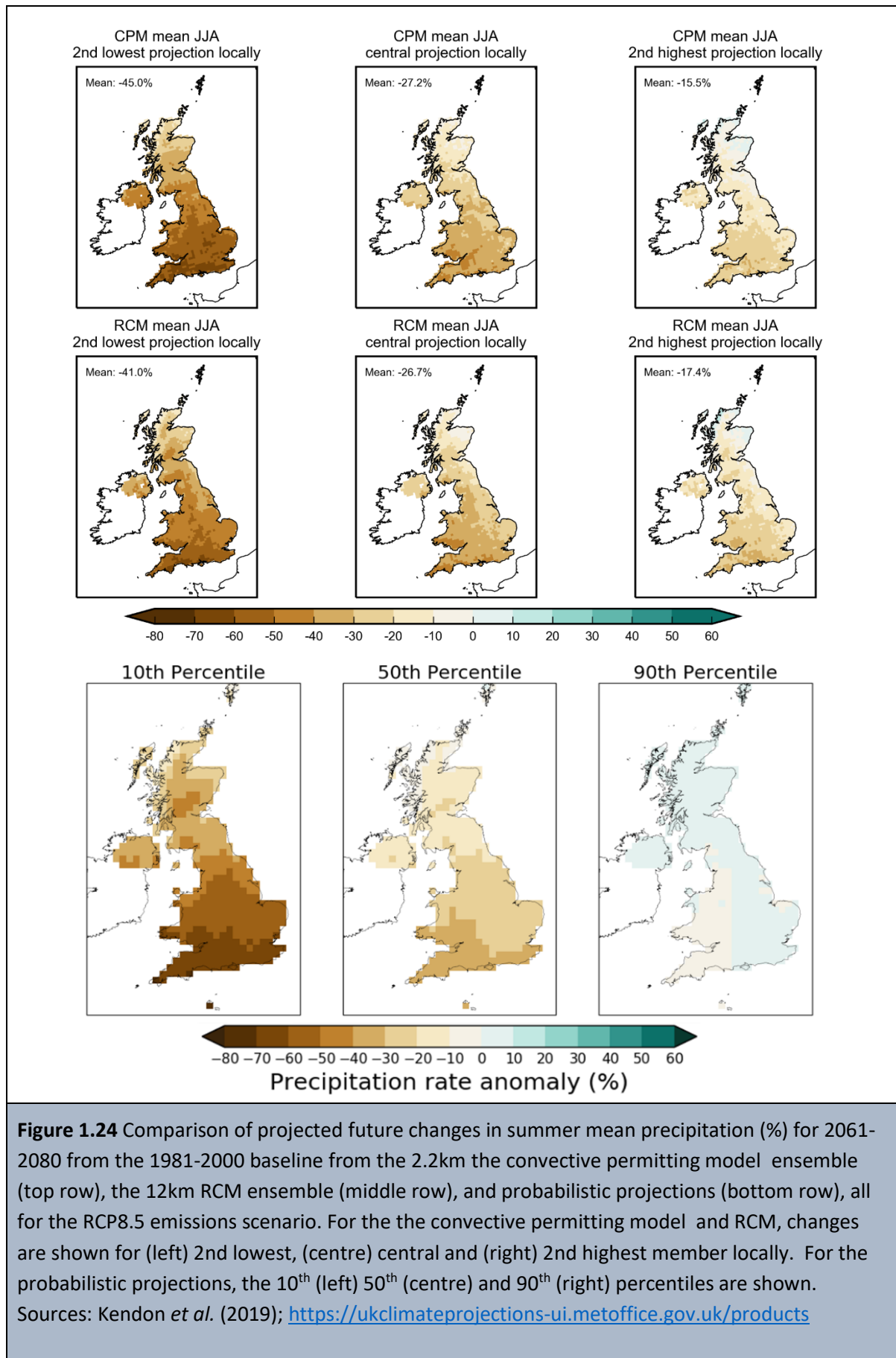
**Figure 1.23** Comparison of seasonal mean changes in surface air temperature (°C) and precipitation (%) across the different UKCP18 products and components, using projected changes with RCP8.5 scenarios, for 2061-2080 relative to 1981-2000, for Scotland and England. (a) and (b) show the changes for summer and (c) and (d) those for winter. Box and whiskers denote the probabilistic projections (Land Strand 1); orange and blue dots denote the HadGEM3 (GC3.05-PPE) and CMIP5 (CMIP5-13) projections respectively. The pink and green dots show the 12km regional model (RCM) and 2.2km convective permitting model projections which use HadGEM3 boundary conditions. The solid dots correspond to the 'standard' HadGEM3 simulation within the full ensemble. The probabilistic projections, GC3.05, RCM and the convective permitting model all use the RCP8.5 emissions scenario and a range of CO<sub>2</sub> concentration pathways accounting for uncertainties in carbon cycle feedbacks. As noted in Section 1.2.3, CMIP5-13 uses a single CO<sub>2</sub> concentration pathway, the standard RCP8.5 concentration pathway, which is at the lower end of the range of the concentration pathways used for the other projections. Reproduced from Kendon, *et al.* (2019)

The introduction of the convective permitting model is particularly important. With kilometre-scale resolution, the convective permitting model not only represents the landscape more accurately, but also captures the fundamental physics of thunderstorms and of embedded convection within weather fronts that is missing in lower resolution models (Kendon *et al.*, 2014). Consequently the representation of extreme sub-daily rainfall and other local extremes, such as wind gusts and high temperatures, has been transformed compared with previous CCRAAs.

In summer, the regional projections are substantially different from the probabilistic projections which incorporate information from CMIP5. HadGEM3 projects hotter and drier summers, a signal that is carried through into the RCM and the convective permitting model results (Figure 1.23(a)). Future increases in temperature over both Scotland and England are projected to be 1-2°C greater than the CMIP5 models. This is associated in part with HadGEM3's higher climate sensitivity and partly with the use of higher CO<sub>2</sub> concentrations in HadGEM3 than CMIP5, because the HadGEM3 projections account for uncertainties in climate-carbon cycle feedbacks (see Annex 1, Figure A1.3 and section A1.4). For England, there is also a very strong signal for much reduced rainfall in summer (Figure 1.23(b)), which itself will also act to elevate summer temperatures. Some of the summer heating may be due to HadGEM3's higher climate sensitivity and higher CO<sub>2</sub> concentrations, but some is clearly associated with changes in the summer atmospheric circulation in HadGEM3 (see Section 1.5.4).

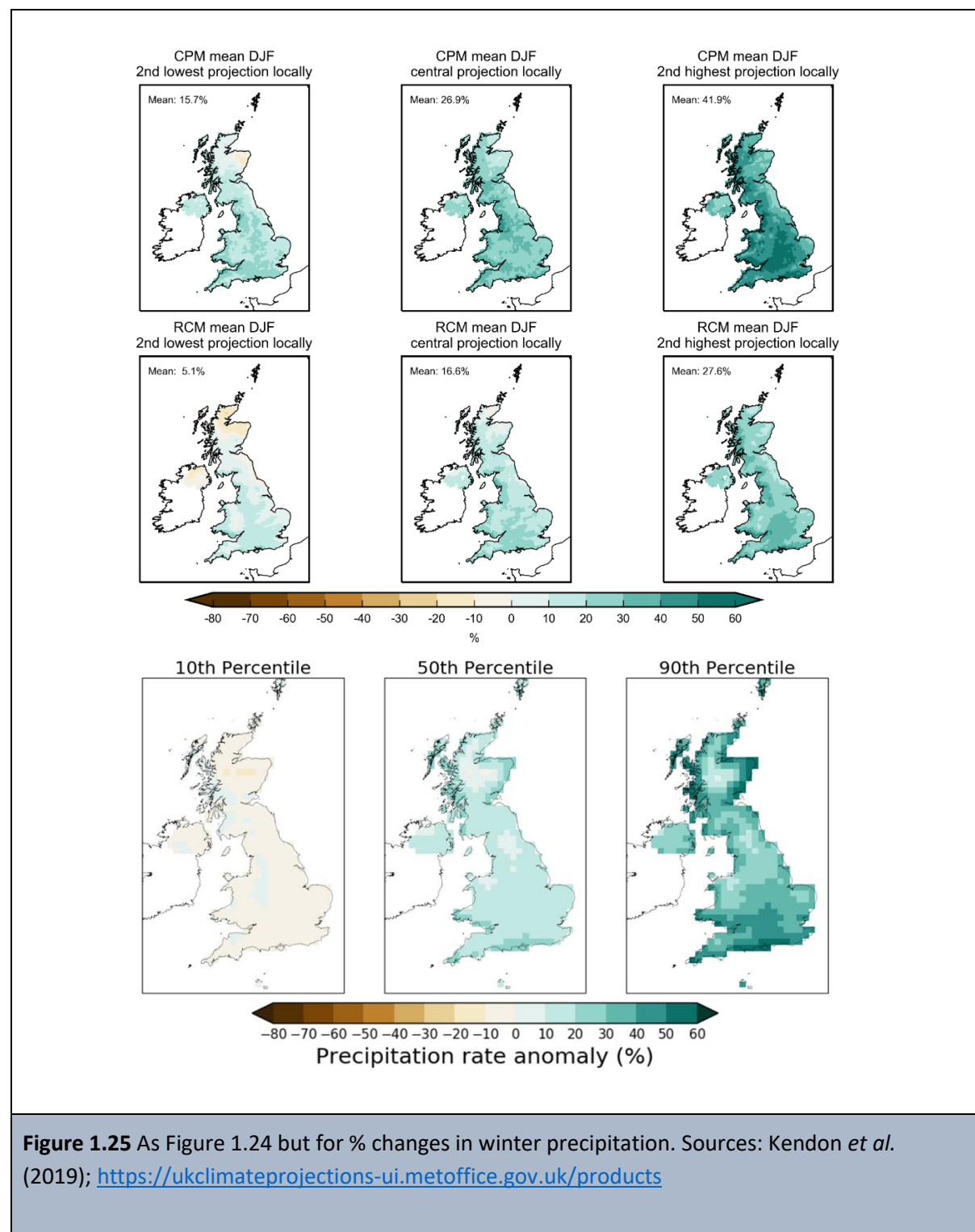
To provide more regional detail, Figure 1.24 compares future changes in the mean summer rainfall from the RCM and the convective permitting model. They are fairly similar which reflects the importance of the driving boundary conditions from HadGEM3. Figure 1.24 also compares these with the 10<sup>th</sup> to 90<sup>th</sup> percentile ranges in the probabilistic projections and shows that this range is larger than those in the RCM and the convective permitting model. While most project decreased precipitation, the probabilistic projections include the possibility of small increases in average summer precipitation over larger areas of the country than in the RCM and the convective permitting model ensembles.





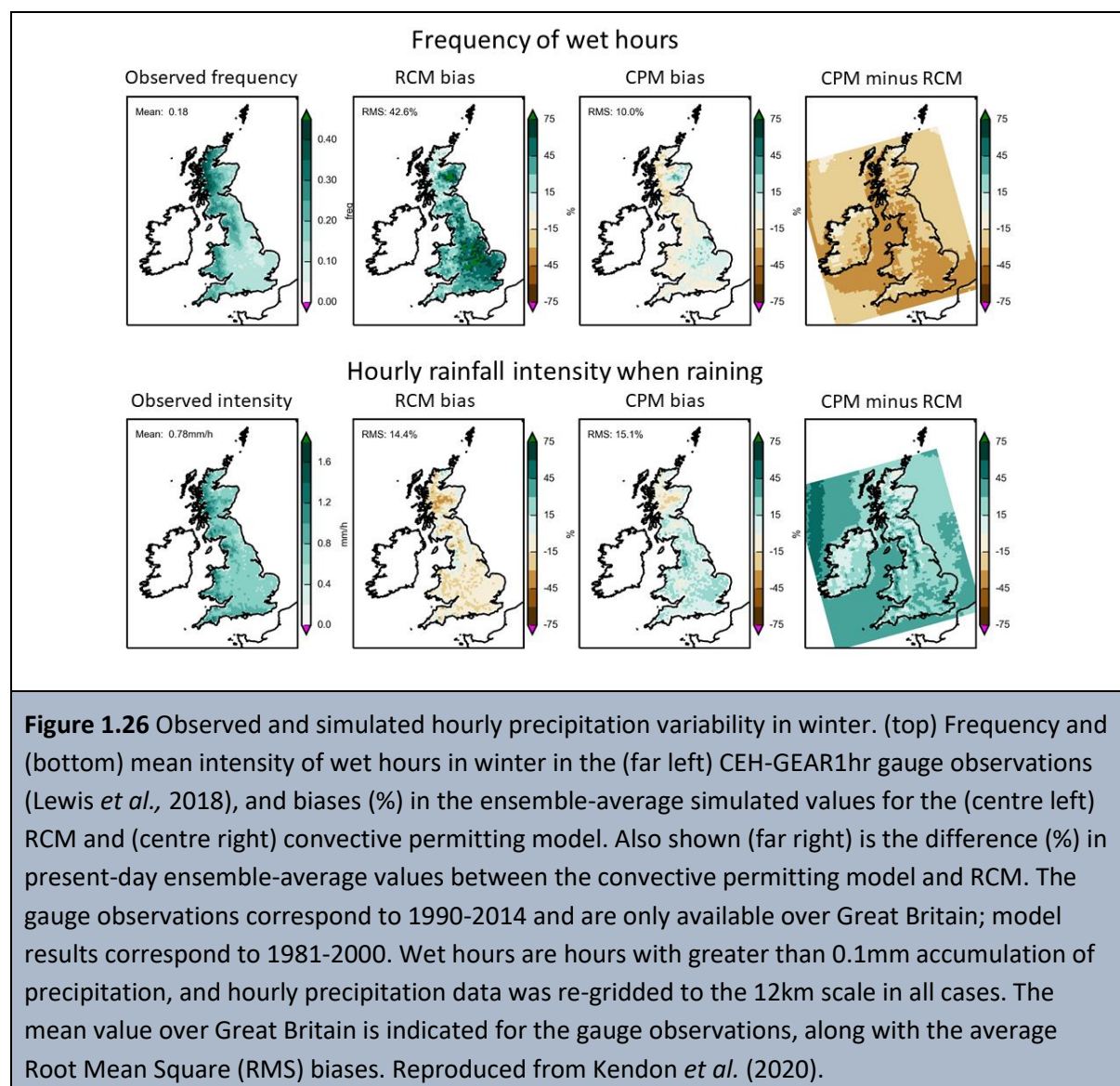


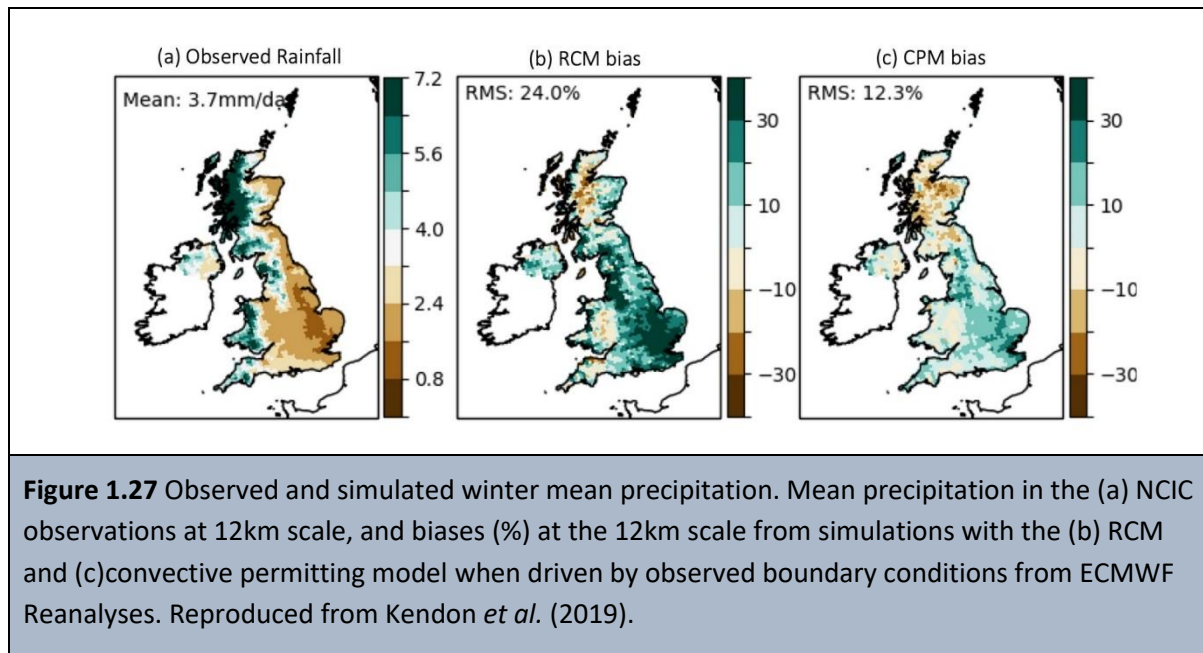
In winter, as shown in Figure 1.23, the results from the various models lie mostly within the range of the probabilistic projections. However, the convective permitting model results show a shift to bigger increases in average precipitation in winter (Figure 1.23) which is countrywide (Figure 1.25).



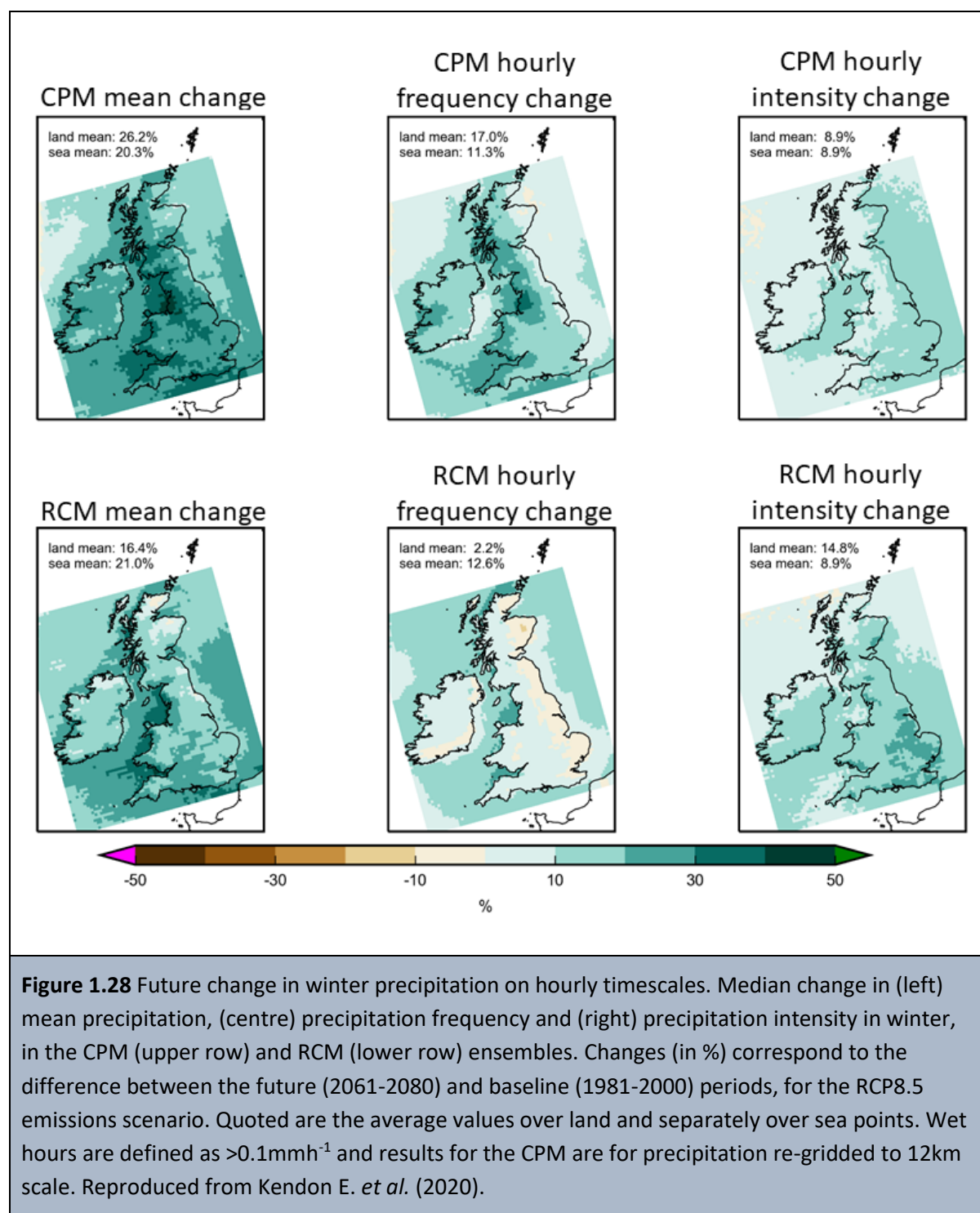
Kendon *et al.* (2020) have linked this increase in winter precipitation in the convective permitting model to the advection over land of convective showers initiated over the sea, a process that lower resolution models do not capture. As in observations, these showers penetrate much further inland in the convective permitting model, bringing more rainfall to the eastern side of the country.

This signal is part of a fundamental difference between the RCM and the the convective permitting model in the nature of winter precipitation. A comparison of hourly precipitation diagnostics with a new observational dataset of hourly precipitation amounts (CEH-GEAR1hr, Lewis *et al.*, 2018) for the current climate (Figure 1.26) shows that the RCM has far too many days when it is raining, and that on those days the rainfall intensity is too low. These biases are largely rectified in the the convective permitting model through *better* representation of the physical processes, as discussed above, giving a simulation that is much closer to observations (Kendon *et al.*, 2020). As a result, the simulation of mean winter precipitation in the the convective permitting model is superior to the RCM for the current climate in a clean test using observed boundary conditions from the ECMWF Reanalyses (Figure 1.27).





Kendon *et al.* (2020) go on to show that, under climate change, the convective permitting model gives both more frequent and more intense rainfall in future over land (Figure 1.28). The frequency increases are considerably larger than in the RCM, with a large part of the convective permitting model's future increases coming from a higher frequency of convective showers. These showers are most likely triggered over the sea (where the warmer ocean and higher levels of atmospheric moisture favour more triggering of convection), and then advected inland, persisting for longer and potentially further development over land. Consequently, as Kendon *et al.* (2020) explain, these showers are an important contributor to the higher winter precipitation response in the convective permitting model; changes in the mean precipitation from convective showers contribute about 40% of the overall change in winter over land in the convective permitting model.



These are important results; they suggest that previous CCRA based on traditional coarser-resolution climate models may underestimate future increases in winter precipitation, especially where wintertime convective showers are a key contributor, since the processes important for the advection and further triggering of showers are only well captured in CPMs. These differences in precipitation frequency and intensity will undoubtedly affect the hydrological response to future rainfall changes, and potentially have implications for river flows, flood risk and water resource management.

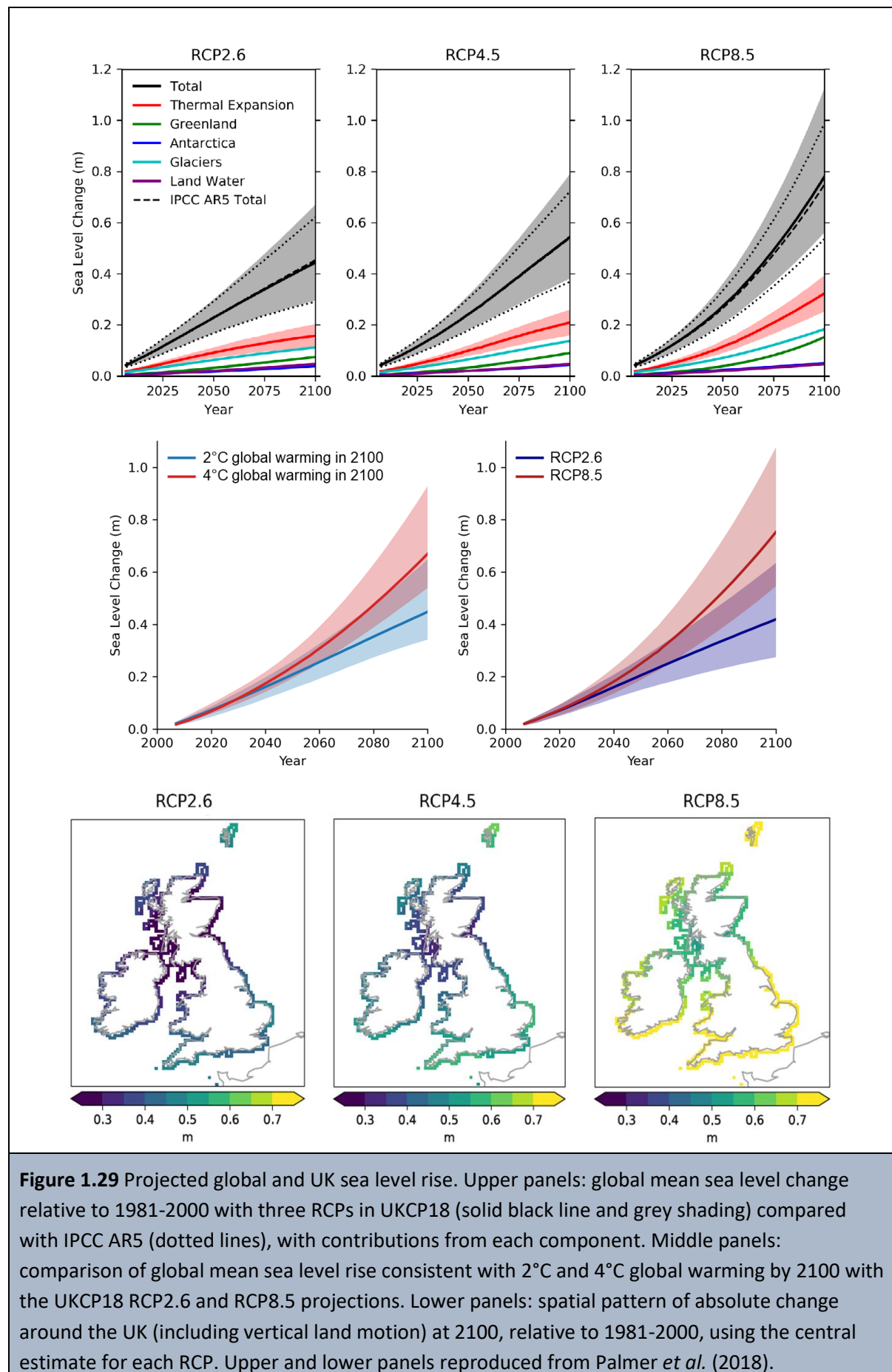
Sea level rise is an important climate impact driver for the UK. Since CCRA2, new assessments of the contributions to current and future sea level rise from the major Greenland and Antarctic Ice Sheets have been derived from observations (suggesting accelerating mass loss) and included in the future projections. Additionally, there have been improvements in the methodology for estimating the range of uncertainties in the UK estimates of local sea rise level (Palmer *et al.*, 2018; Palmer *et al.*, 2020).

Figure 1.29 (upper panels) shows the evolution of global sea level rise through the 21<sup>st</sup> century in the UKCP18 marine projections, using CMIP5 climate scenarios with three concentration pathways. The contributions to sea level rise from the various components are also shown. As in the observations, the thermal expansion of seawater only contributes around one third of the total, emphasising the importance of understanding the vulnerability of the major ice sheets and how mass loss will evolve.

The new estimates in Figure 1.29 include updated estimates of the contribution from Antarctic ice dynamics, which have led to a substantive change in the projections, especially for the 95<sup>th</sup> percentile, indicating an additional 5 - 10cm rise in sea level by 2100 compared with earlier estimates also based on CMIP5 climate projections. However, the processes behind ice sheet collapse particularly for Antarctica remain very uncertain and continued monitoring and process studies are vital. The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019) highlighted that global sea-level rise by 2100 could reach 2m in the most extreme scenarios but viewed this as very unlikely and with low confidence (See Section 1.8 on Earth System Instabilities).

Both the UKCP18 and IPCC AR5 sea-level projections use the CMIP5 climate projections, with UKCP18 using updated methods to project sea level rise resulting from the projected climate changes. It is important to note that the CMIP5 models are driven by the standard RCP projections of concentrations of CO<sub>2</sub> and other greenhouse gases, in contrast with the UKCP18 land projections which are driven by emissions scenarios and account for uncertainties in carbon cycle feedbacks (see Annex 1 A1.4). This means that for any given RCP, the sea level rises in the UKCP18 marine projections are mostly driven by a slower rate of global warming than represented in the UKCP18 land projections (see Figure 1.2).

When subsets of the UKCP18 sea level rise projections consistent with global warming of 2°C and 4°C ( $\pm 0.1$  °C) in 2100 are extracted, these are found to cover much of the likely range of the projections with the RCP2.6 and RCP8.5 concentration pathways (Figure 1.29 middle panels). Therefore the RCP2.6 and RCP8.5 sea level projections can be considered to be reasonably representative of sea level rise consistent with pathways to global warming of 2°C and 4°C ( $\pm 0.1$  °C) in 2100. The RCP8.5 central estimate is about 0.1 m higher than that of the sea level projection consistent with 4°C warming in 2100.





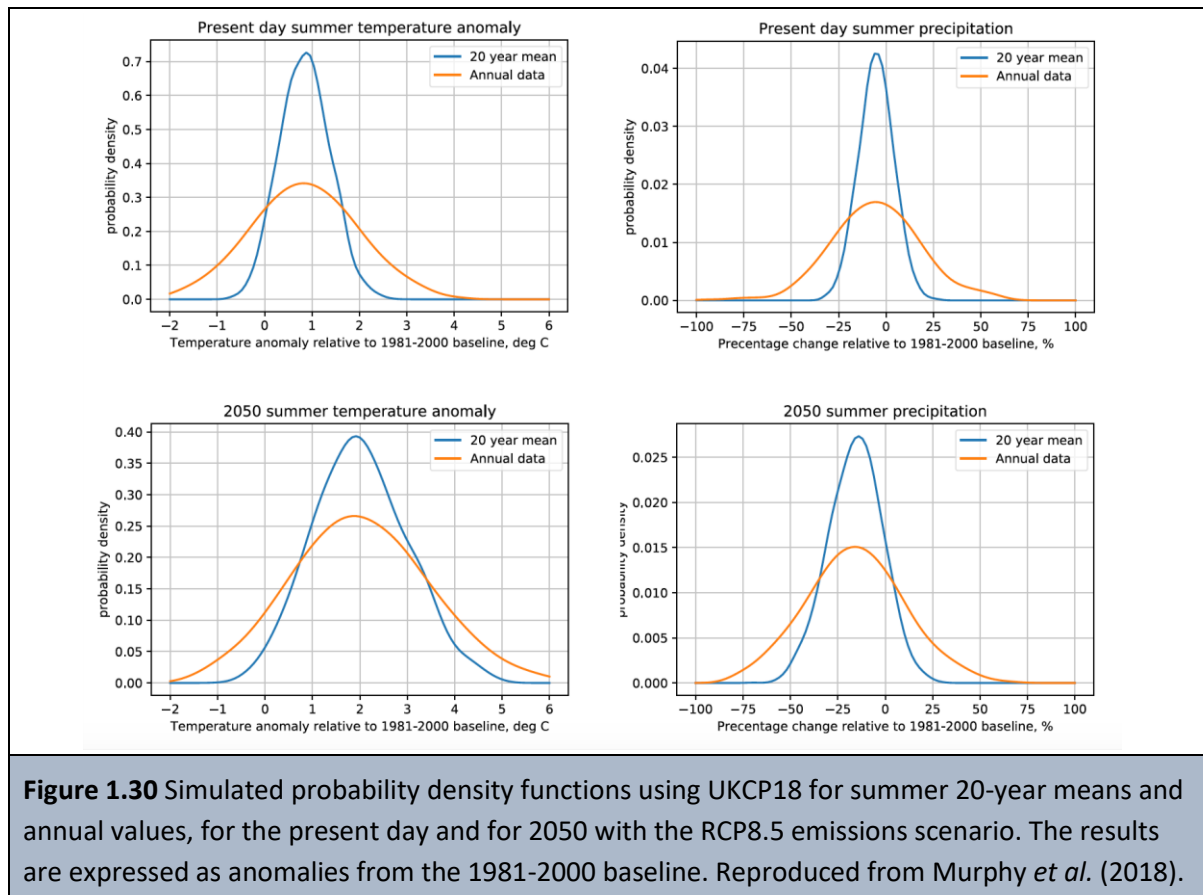
The lower panels of Figure 1.29 show the regional variations in median sea level rise around the UK with the familiar pattern of higher changes in the south. These variations occur due to land-based ice and land water mass loadings, changes in the ocean circulation and the ongoing isostatic adjustment to the last glacial maximum.

Beyond rises in mean sea level many coastal impacts are associated with storm surges. The latest evidence suggests that changes in extreme water levels will likely be more driven by changes in mean sea level than changes in surge, although notable changes in surge (+ or -) cannot be ruled out (Palmer *et al.*, 2018).

### **1.5.3 Moving beyond average climate change: The importance of climate variability on annual timescales**

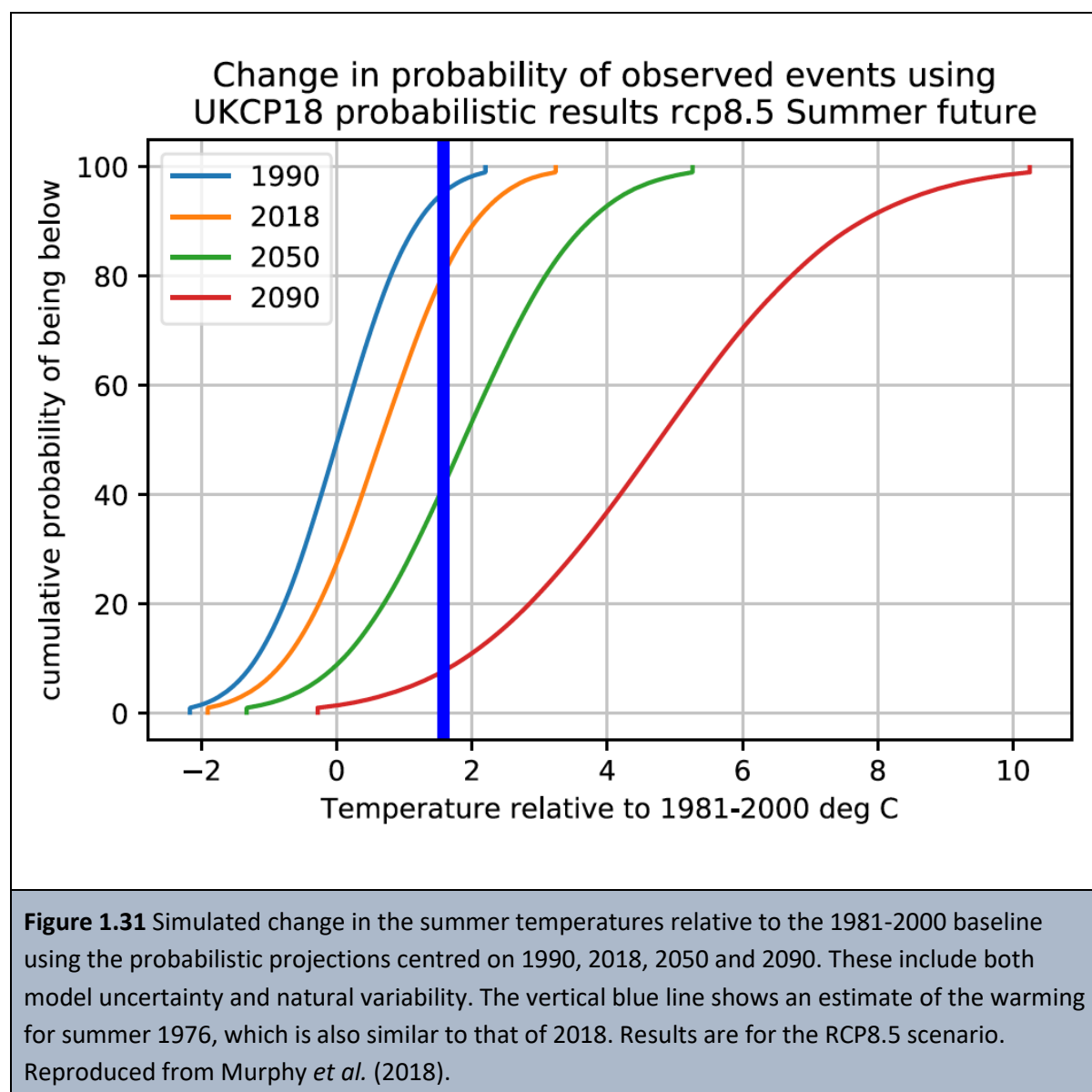
There is far more evidence in UKCP18 regarding the volatility of the UK's weather and climate going forward, and this provides an improved evidence base for assessing future risks (e.g., Sexton and Harris, 2015). An important new element in UKCP18 is the inclusion of estimates of the envelope of interannual variability; these act to broaden the distribution of probabilities and provide information on changes in the likelihood and intensity of extreme months or seasons going forward.

When interannual variability within any long-term average is included, the spread in the various climatic impact drivers is increased significantly, particularly for variables, such as precipitation, that are highly variable in space and time (Figure 1.30). As Sexton and Harris (2015) note, the spread associated with natural variability is larger for near term climate change, when the forced changes and their inherent uncertainties are smaller. As Figure 1.30 demonstrates, individual summers have high likelihoods of being either wetter or drier than the 20-year average would suggest.



By including the interannual variability in UKCP18 it is possible to look at specific extreme years from the past and to estimate the probability of experiencing such events in the future. Figure 1.31 shows how the probability of experiencing a hot summer like 1976 or 2018 changes with time through the 21<sup>st</sup> century for the RCP8.5 pathway. By the middle of the century the probability of a summer as warm or warmer than 1976/2018 has a projected probability of around 50%, while by the end of the century the probability is greater than 90%; in other words, summers like 1976 and 2018 could become commonplace.





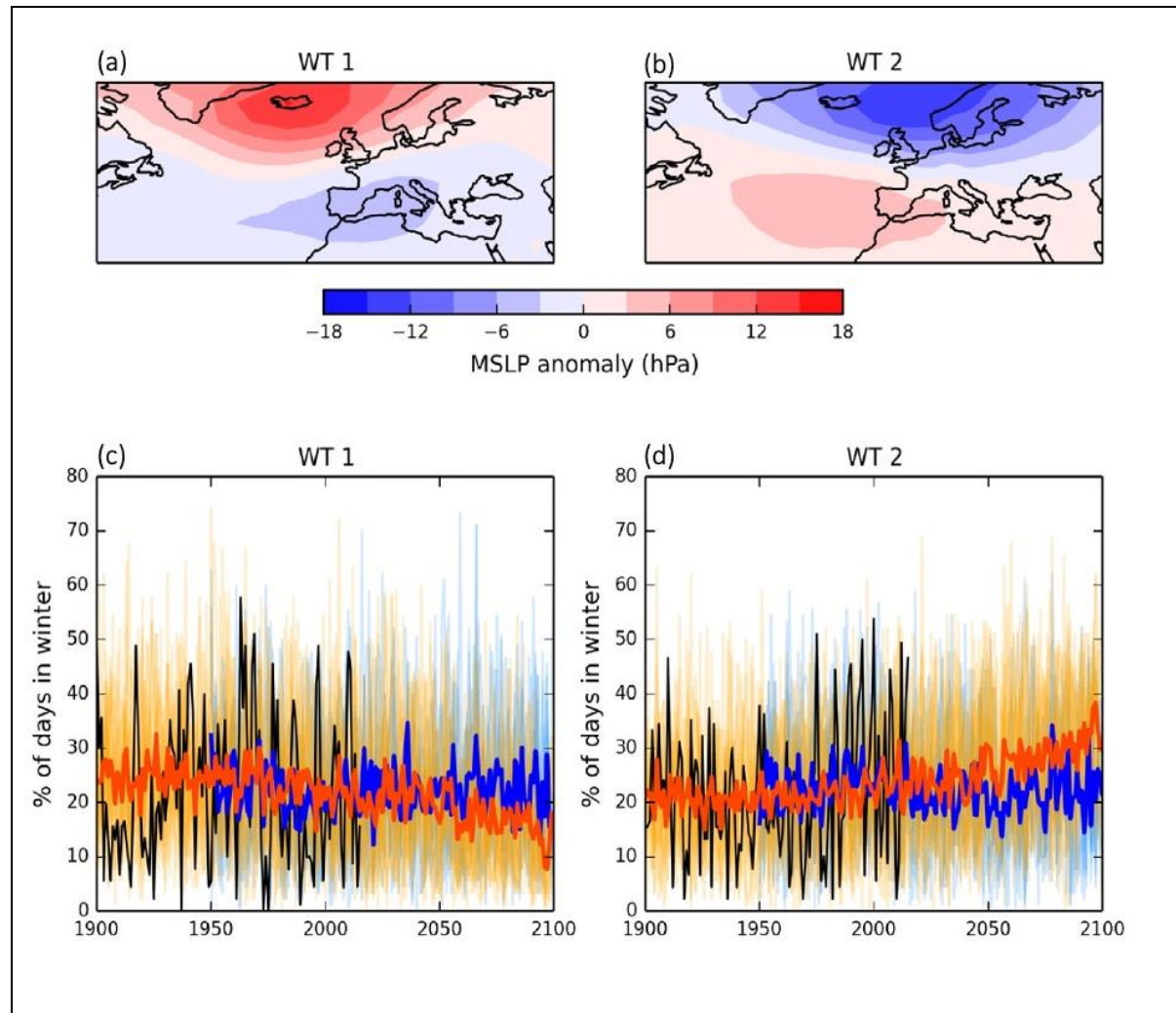
In summary, UKCP18 has delivered a new capability to look beyond changes in the mean climate to consider shifts in the envelope of interannual variability. This provides a much richer evidence base for assessing future climatic impact drivers and provides important links between what we experience today and what we will experience in the future.

#### 1.5.4 Moving beyond average climate change: The importance of weather regimes under climate change.

As discussed in Section 1.2, it is important to look beyond simple metrics of average climate change to consider changes in prevailing weather patterns. As outlined in Section 1.2 and documented in Annex 1, HadGEM3 is a more skilful model in representing the North Atlantic Jetstream, its variability and related weather regimes, which may have a strong influence on the UK's future weather and related impacts. For example, Senior *et al.* (2016) investigated the impact of increasing resolution in HadGEM3 on climate change simulations and noted that although long-term averages

at continental and large scales were largely unchanged, there were important regional impacts, including a greater increase in the frequency of the most intense winter storms at the higher resolution used in UKCP18.

In winter, the UK's weather is dominated by the phase of the North Atlantic Oscillation (NAO), which gives rise to two distinct Weather Types (WT), describing either blocked, colder and drier winters (WT 1) or warmer, wetter and windier winters (WT 2; Figures 1.32(a) and (b)). One of the striking results from UKCP18 is the difference between the CMIP5 and HadGEM3 ensembles in the population of these two distinct weather regimes through the 21<sup>st</sup> century (Figures 1.32(c) and (d)).



**Figure 1.32** Past and future behaviour of the two dominant winter daily weather patterns (WT1 and WT2) that affect the UK, based on the phase of the North Atlantic Oscillation (NAO) and as identified by Neal *et al.* (2016). (a) and (b) show the observed anomalies (hPa) in mean sea level pressure (MSLP) relating WT1 and WT2. Together they describe the negative (a) and positive (b) phases of the NAO. (c) and (d) show the percentage of winter days assigned to each pattern for nine members of the CMIP5-13 ensemble with the RCP8.5 concentration pathway (blue) and the HadGEM3 GC3.05 ensemble with RCP8.5 emissions (orange). The thicker lines show the ensemble mean and the black line represents the historical values. Reproduced from Murphy *et al.* (2018).

Both ensembles capture the mean and year-to-year variability of the observations reasonably well, bearing in mind the short observational record and multi-decadal fluctuations in the NAO. However, whereas CMIP5 suggests no change in the population of these weather types, HadGEM3 shows clear trends towards WT 2 and away from WT 1. This implies that future winter weather may be dominated by more mobile, cyclonic weather systems, with fewer blocked winters. This will affect the western parts of the UK, in particular, and may contribute to more substantial increases in daily precipitation with related flooding, as well as a higher incidence of strong winds and waves. As well as the severity of flooding, its special extent is also higher under the types of strong westerly airflow that are expected to become more common (Wilby and Quinn, 2013).

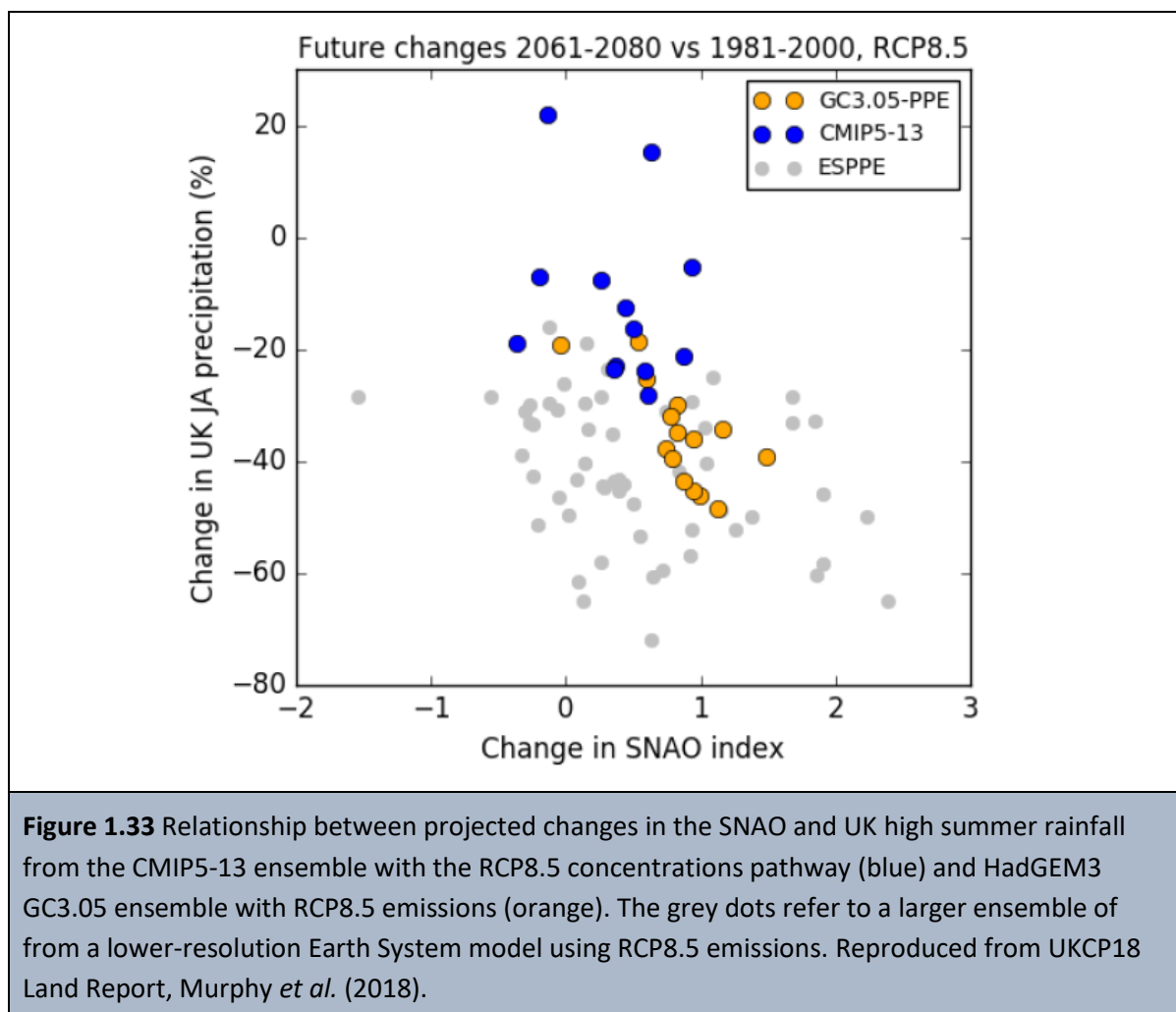
The projected shift to more mobile, cyclonic winters may also increase the risk of atmospheric river events that bring large amounts of precipitation and are major contributors to severe flooding, particularly for the mountainous regions of the UK (e.g., Lavers *et al.*, 2011). Storm Desmond in 2015 was a notable example, with the classic streamer of moist air being drawn from the Caribbean, carried by a strong Jetstream, and impinging on the mountains of Lake District.

Matthews *et al.* (2018) argue that the long-term warming of the North Atlantic may have increased the chance of such an atmospheric river event. Similarly, a recent study by Payne *et al.* (2020), shows that climate change is likely to increase the frequency of atmospheric river events which, when combined with increased atmospheric moisture due to warming, may make them even more severe, increasing the risk of serious flooding and landslides.

This is important new evidence. Even though average annual trends suggest minimal differences in mean winter precipitation between CMIP5 and HadGEM3, changes in the population of these weather regimes may lead to different impacts associated with storms and heavy rainfall, for example.

As in winter, UK summers are also affected by the population of specific weather regimes. Extreme summer heat, as experienced in 2018, was due mainly to a strongly positive summer NAO (SNAO; e.g. Folland *et al.*, 2009), which is characterised by a high-pressure anomaly over and to the north-east of the UK. The positive phase of the SNAO corresponds to anomalous easterly winds, which bring warm air from continental Europe, as well as more local solar radiation and surface sensible heating. These effects reinforce the temperature response over the UK, resulting in the SNAO being a very important control on UK summer heat.

In addition to influencing summer heat, the SNAO is also an important driver of summer rainfall anomalies. Folland *et al.* (2009) showed that there is a strong, negative correlation between the SNAO and England-Wales precipitation, with a positive SNAO favouring low summer rainfall. Studies of the future behavior of the SNAO have shown a tendency for more positive phases under a warming climate, which would indicate an increased prevalence of high temperatures and drought in the future. However, there are large discrepancies between the change in the SNAO and its projection on to UK precipitation, between the CMIP5 models and HadGEM3 (Figure 1.33). Whereas some of the CMIP5 models suggest increased rainfall with a shift to more positive SNAO conditions, HadGEM3 shows a clear signal for reduced rainfall, consistent with the observed relationship between the SNAO and rainfall.



The strong reduction in precipitation in HadGEM3 in response to changes in the circulation, may therefore be a contributing factor in generating more extreme high temperatures in future summers compared with previous projections. Although more research is needed to understand the physical mechanisms behind these changes in the SNAO and its projection on to UK precipitation, it is important that CCRA3 considers the possible impacts of these more extreme scenarios.

Heatwaves and drought are not the only hazards related to the projected change in the summer climate. Wildfires are increasingly likely and potentially more severe (Arnell *et al.* 2021). Poor air quality, linked for example to surface ozone, is exacerbated by high temperatures (Doherty *et al.*, 2013) and by the prevalence of continental air masses which occur during summer blocking episodes (Royal Society, 2008).

The clear message emerging from these studies is that atmospheric circulation patterns (i.e., weather regimes on timescales of days to weeks and modes of climate variability on timescales from months to decades) remain the dominant influence on UK climate impact drivers, now and into the future. Projections of UK climate change therefore need to be underpinned by climate models that have the capability to reproduce these atmospheric patterns, their spatial and temporal characteristics, if they are to tell us how these may change in a warming world.

This is only now beginning to be realised with the latest generation of high-resolution global climate models although many issues still remain. UKCP18 is the first set of UK climate projections to exploit this new generation of high-resolution projections that can begin to answer the question of what the UK's weather will be like in the future and what this means for our future risks and opportunities.

### 1.5.5 Moving beyond average climate change: Daily climatic impact drivers and extreme events

Changes in daily weather and related short-timescale extremes are a key component of many climatic impact drivers. They are typically localized and hence challenging for global and even regional models, with their coarse granularity, to provide reliable estimates. Through the innovative use of the 2.2km convection permitting model UKCP18 has delivered some important new insights on local climatic impact drivers, not just confined to extremes, but including the impacts of representing convection on winter mean precipitation changes (see Section 1.5.2).

So far, the focus of the convection permitting model results has been on high temperatures and extreme rainfall, but other information (for example on wind extremes, hail and lightning) will gradually emerge as the convection permitting model projections are analyzed further.

#### 1.5.5.1 Extreme Temperatures

The UK record temperature of 38.7°C set in Cambridge in July 2019 has raised the question of whether exceeding 40 °C is possible. A frequency analysis of exceedances for specific high temperature thresholds in the RCM and convection permitting model ensembles, versus the NCIC observations, is documented in Table 1.1. The results are expressed as the number of counts of threshold exceedances for all points (based on 12km grid) and for all days in a 20-year period, across the UK (upper table) and just for London (lower table). Table 1.1 shows the median value and also the range across the model ensembles; these indicate quite a broad spread in the models which, for the current climate (1981-2000), generally encompasses the observations. It is worth noting that counts of 4871 and 184 for the 32°C threshold in the present-day simulation of the convection permitting model, for all-UK and London respectively, correspond to only 0.04% and 0.21% of values. Therefore exceedances of these thresholds are very much in the tail of the temperature distribution and hence subject to quite a bit of noise, especially with only a small model ensemble.

**Table 1.1** Counts of exceeding certain daytime temperatures for 20-year periods from NCIC observations, the RCM and convection permitting model, for all gridpoints over the UK (1614 points; upper table) and London (12 points; lower table) over all days for the current climate (1981-2000) and for future projections (2021-2040; 2061-2080) using the RCP8.5 scenario. All data have been regridded to 12km RCM grid. Thus, the total number of days is 7200 days for the models (360-day calendar) and 7305 days for the observations, and the maximum number of counts is therefore 11,620,800 (11,790,270 for the observations) for all UK land points, and 86,400 (87,660) for London. The numbers show the median count (in bold), and the low to high estimate (in brackets, corresponding to

2<sup>nd</sup> lowest to 2<sup>nd</sup> highest member) counts across the ensemble for the convection permitting model and RCM, compared to NCIC observations, for the 20 years of each timeslice. Source: Met Office.

#### ALL UK

Threshold (°C)	32	35	38	40
OBS (1981-2000)	2119	108	0	0
CPM (1981-2000)	4871 (1999,8032)	883 (37,1265)	1 (0,208)	0 (0,0)
RCM (1981-2000)	1199 (139,10584)	38 (2,984)	1 (0,7)	0 (0,2)
CPM (2021 – 2040)	26798 (18985,46989)	6435 (3752,15122)	1(416,3736)	232 (22,966)
RCM (2021 – 2040)	14079 (4926,43211)	2936 (732,10964)	347 (1,1868)	21 (0,126)
CPM (2061 – 2080)	182842 (115971,257960)	64343 (32330,83721)	16850 (6317,22595)	5998 (1955,10052)
RCM (2061 – 2080)	137297 (42261,290801)	39434 (7923,96155)	9223 (1461,21335)	2868 (584,7155)

#### LONDON

Threshold (°C)	32	35	38	40
OBS (1981-2000)	86	8	0	0
CPM (1981-2000)	184 (104,320)	40 (1,50)	0 (0,10)	0 (0,0)
RCM (1981-2000)	67 (24,230)	6 (0,38)	0 (0,1)	0 (0,0)
CPM (2021 – 2040)	944 (694,1476)	204 (144,486)	51 (22,100)	11 (0,34)
RCM (2021 – 2040)	428 (182,1014)	83 (24,259)	14 (1,49)	1 (0,9)
CPM (2061 – 2080)	4949 (3326,6412)	1754 (1022,2267)	476 (227,713)	141 (38,269)
RCM (2061 – 2080)	3259 (1480,5428)	891 (355,1717)	150 (65,362)	41 (19,124)

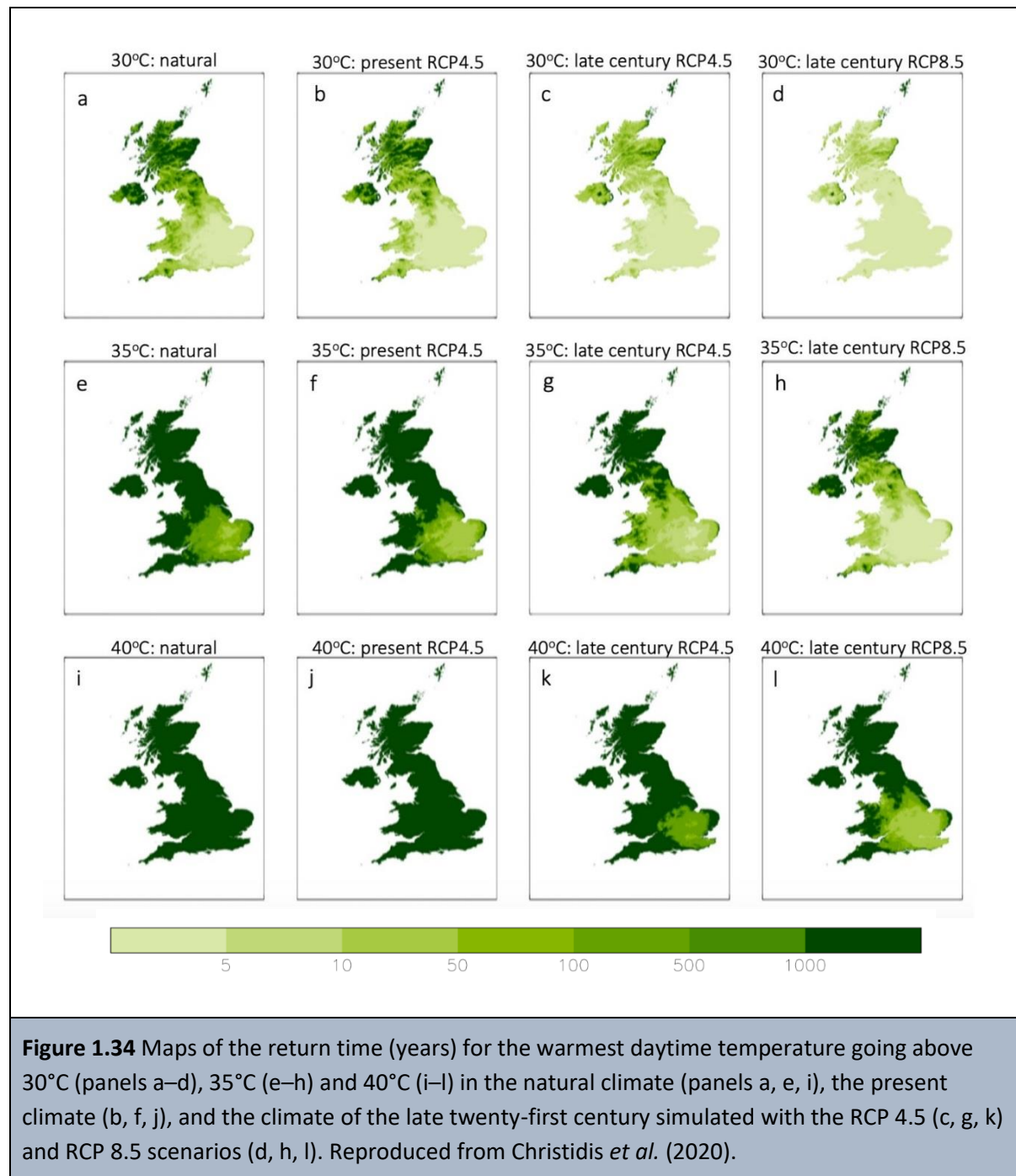
The results in Table 1.1 show a clear signal of increasing frequencies of high temperature exceedances through the 21<sup>st</sup> century, in accordance with the overall warming. The CPM systematically records higher frequencies than the RCM, even though the mean warming is almost identical (see Figure 1.22). However, the convection permitting model provides a better representation of urban processes and heat-island effects, due to both the high spatial resolution and also the use of the 2-tile MORUSES urban scheme. Importantly, both models show that there is a very small chance of exceeding 40°C by 2040, but that by 2080 the frequency of exceeding 40°C is similar to the frequency of exceeding 32°C today with the RCP8.5 concentration pathway<sup>6</sup>.

<sup>6</sup> The median of the RCP8.5 projections with the CMIP5 multi-model ensemble is consistent with a scenario of 4°C global warming at the end of the century: see Chapter 2: Watkiss and Betts (2021).



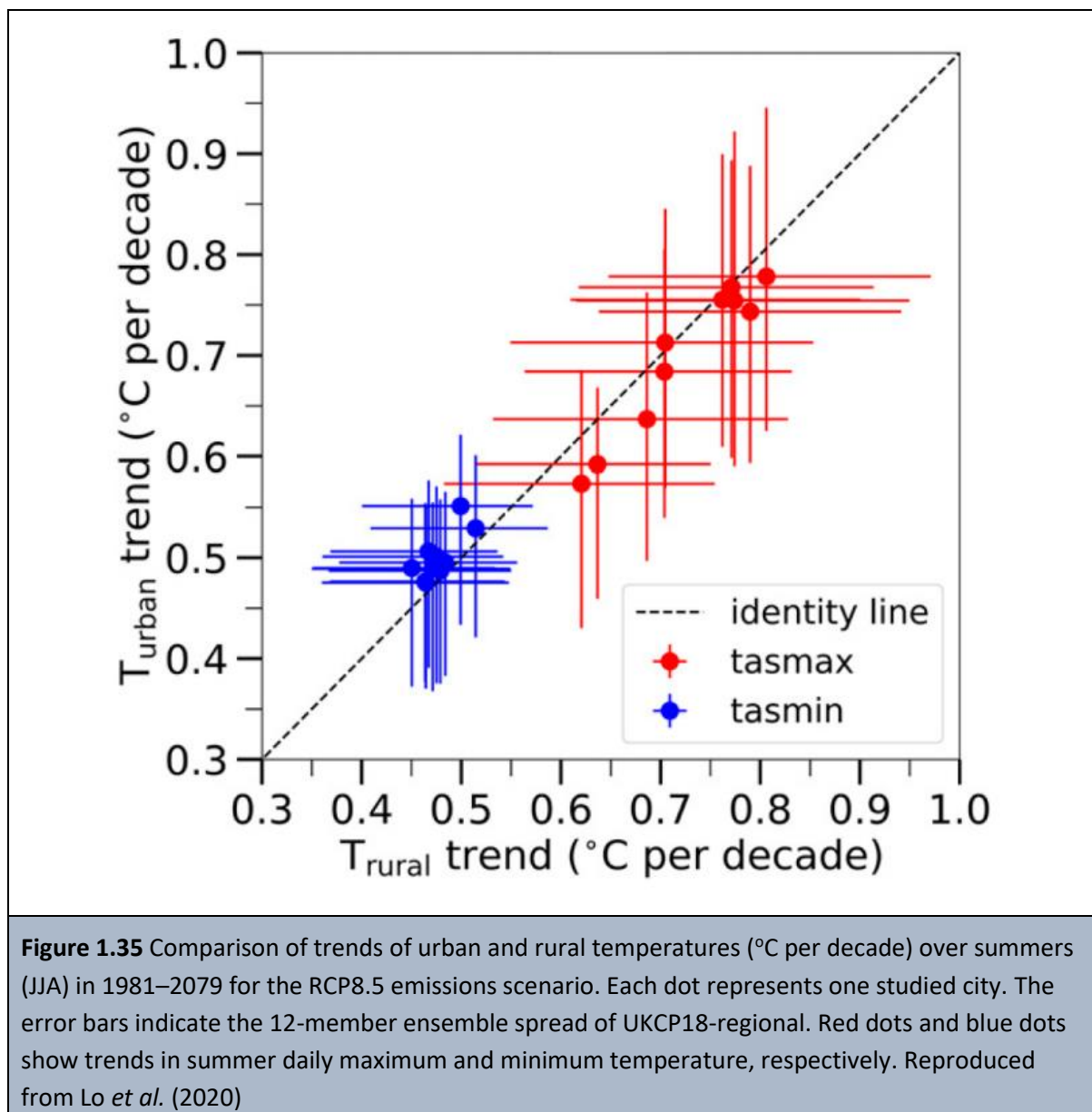
Furthermore, the median likelihood of exceeding 40°C by 2080 is three times higher in London than across the whole of the UK (0.16% versus 0.05%).

The potential for the UK to experience daytime temperatures above 40°C has also been demonstrated in an independent study by Christidis *et al.* (2020) using a different methodology. They addressed the question of high temperature exceedances by using observations to relate local extremes to UK-wide mean extremes, and then applying the resulting relationships to 16 CMIP5 global model projections in a risk-based attribution methodology. This enables them to distinguish between high temperatures due solely to natural variability and those that have a contribution from anthropogenic warming, both for the present day and for the late 21<sup>st</sup> century (Figure 1.34).



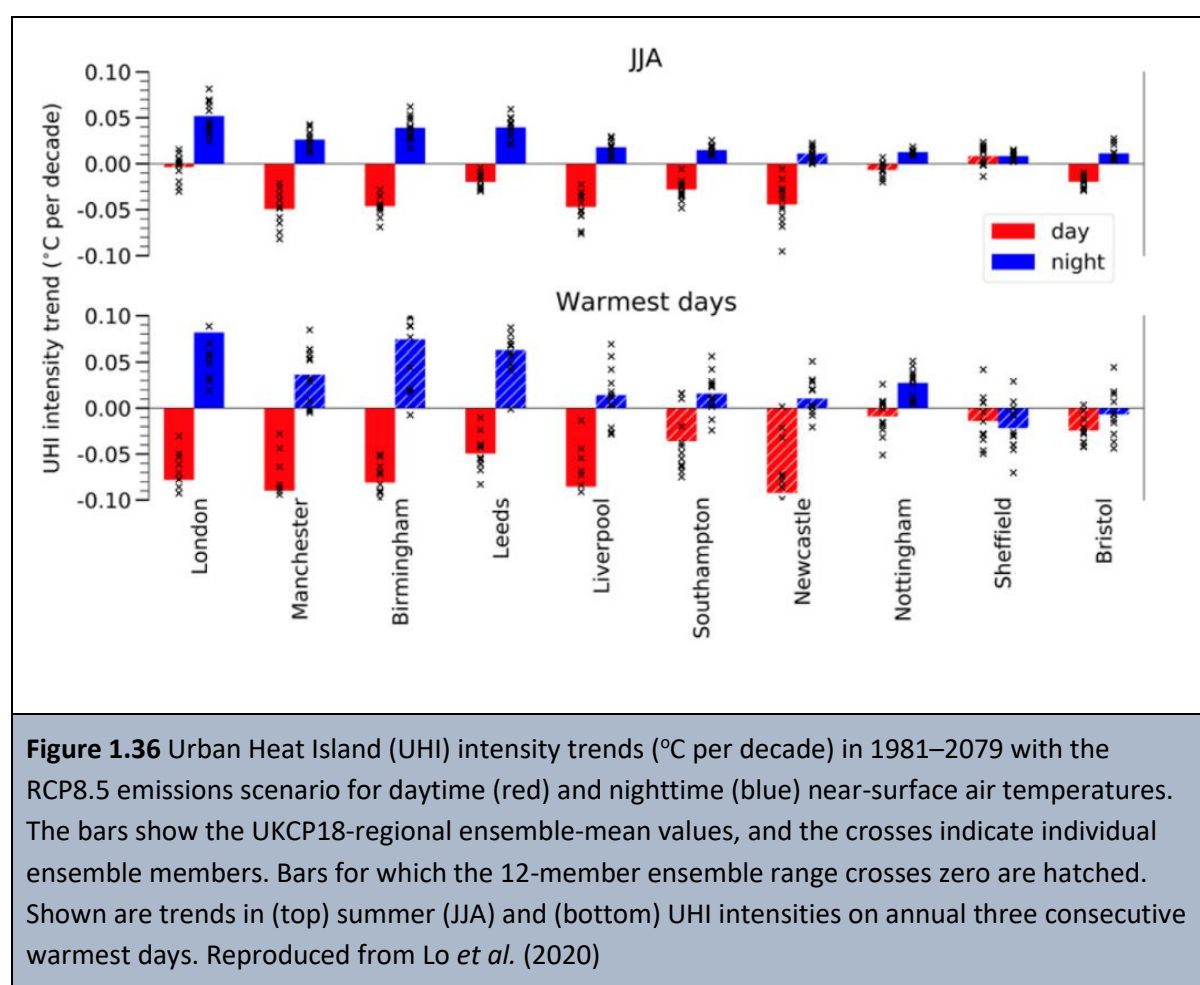
For the present day, the incidence of high temperatures is dominated by natural variability but later in the century human influence dominates. Across the whole of the UK the likelihood, locally, of exceeding 30°C, and even 35°C, increases with time. By 2100 many areas in the north are likely to exceed 30 °C at least once per decade. In the south-east temperatures above 35°C become increasingly common, and temperatures exceeding 40°C also become possible. Summers that experience days above 40°C somewhere in the UK have a return time of 100-300 years at present. This is projected to decrease to 3.5 years by 2100 with the RCP8.5 concentration pathway, which is consistent with a scenario of 4°C global warming at the end of the century (see Chapter 2: Watkiss and Betts, 2021).

Using the UKCP18 RCM projections, Lo *et al.* (2020) have estimated the 1981–2079 trends in summer urban and rural near-surface air temperatures and in urban heat island (UHI) intensities during day and at night in the 10 most populous built-up areas in England. There are larger upward trends in daytime than nighttime temperature for both urban and rural areas (Figure 1.35), where rural areas are defined as those contiguous to the city.





Their results also show a signal of an urban cool island effect during the day but an urban heat island effect during the night (Figure 1.36). For example, by 2080, London's ensemble-mean summer nighttime UHI intensity is projected to increase to 2.1°C, whereas its daytime UHI intensity is projected to decrease slightly to 0.8°C. These summer daytime urban cool islands are likely to be the result of a phase delay in the increase in upward sensible heat flux in the urban areas during the day because of their large thermal inertia (e.g., Bohnenstengel *et al.*, 2014). This means that cities absorb heat during the day and release it at night. The increased intensity of the UHI at night has implications for the frequency of tropical nights in cities with associated heat stress and health implications.

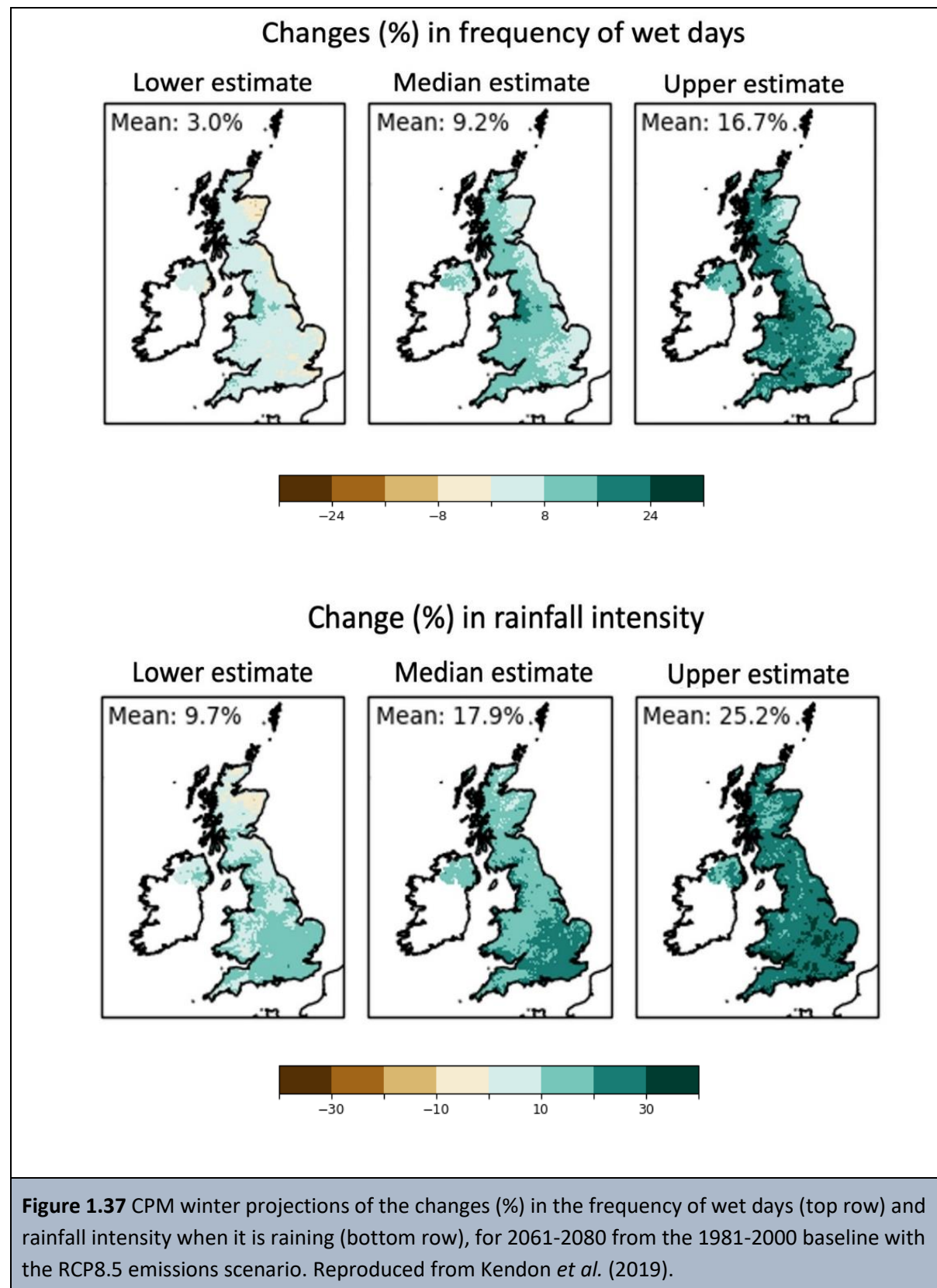


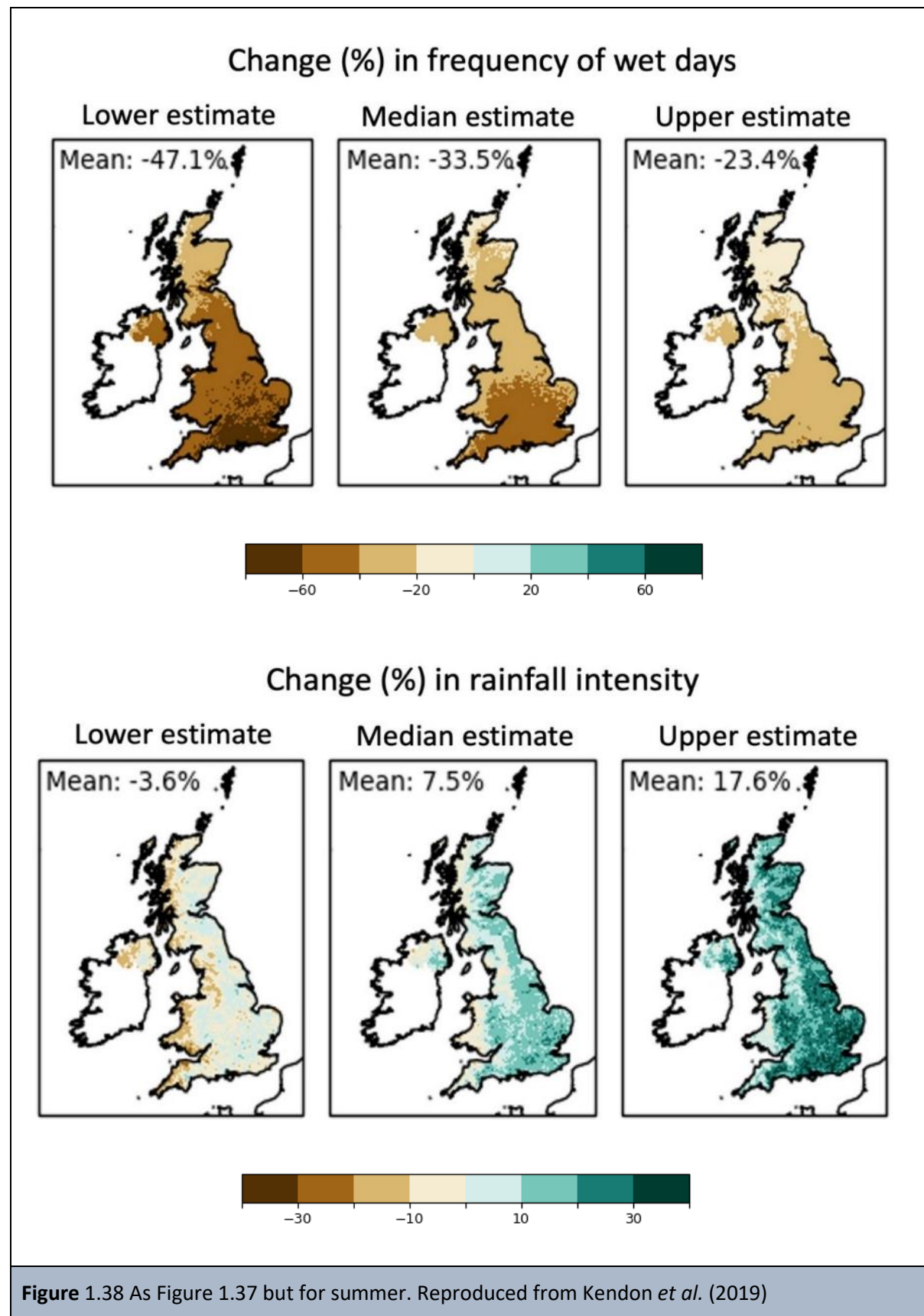
### 1.5.5.2 Extreme Precipitation

The average precipitation is a combination of the frequency of rainfall (often termed wet days) and the intensity of the rainfall when it is raining. Even when the average precipitation is unchanged, there can be shifts between frequency and intensity that have important hydrological consequences. Flooding, water resource management and agriculture are all sensitive to the frequency of rain days and how intense the rain is when it falls.

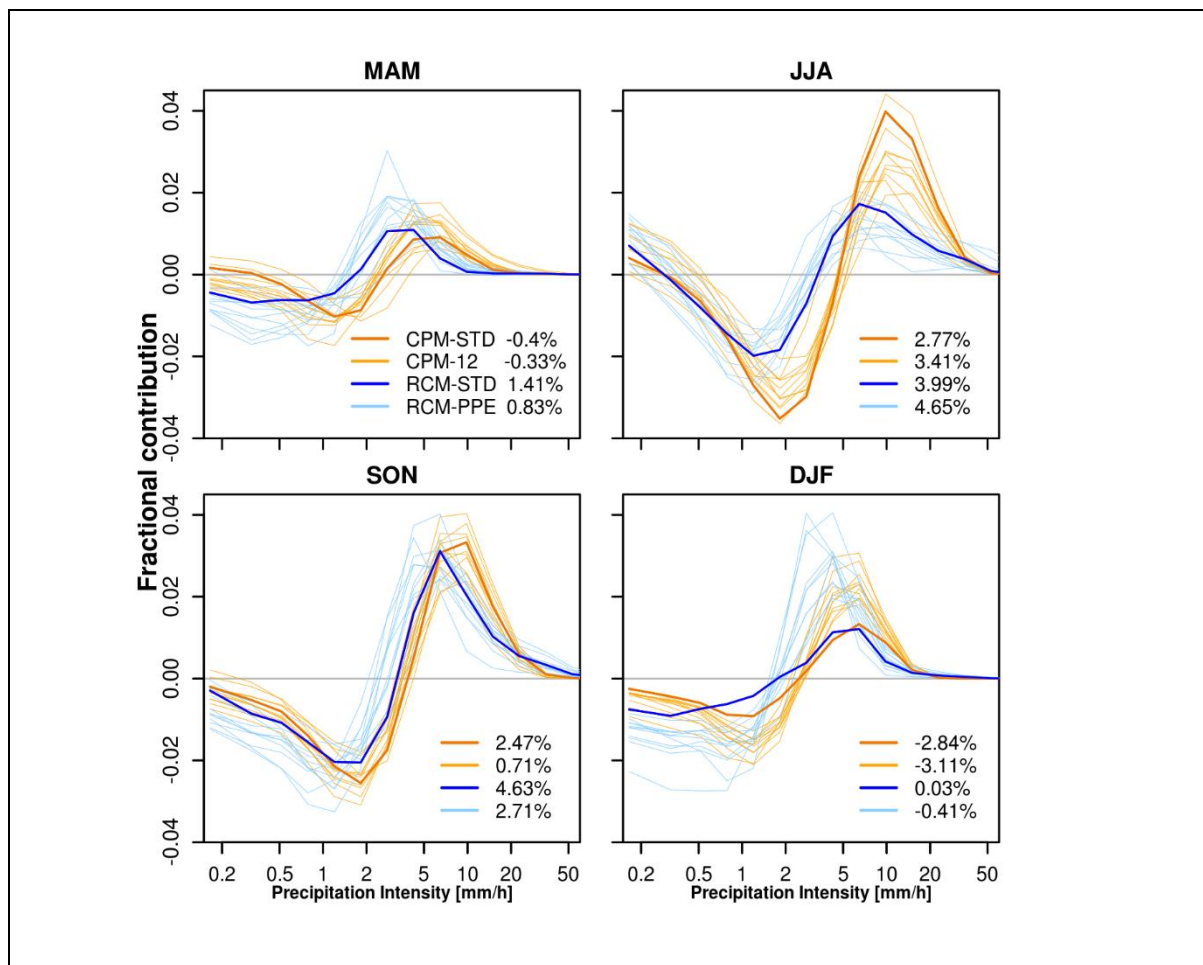
The convection permitting model has proved to be particularly effective in capturing the frequency versus intensity of precipitation (e.g., Kendon *et al.*, 2019) and for simulating extreme daily and sub-daily precipitation (e.g., Kendon *et al.*, 2014). This is because the convection permitting model is able to resolve much more of the physics of rain-bearing systems, as well as resolving the local landscape, especially mountainous terrain, with much greater fidelity than the RCM and global models.

The mean signal of wetter winters is a combination of more wet days (Figure 1.37 top row), as well as an increase in the intensity of rainfall (Figure 1.37 bottom row), which is projected to increase by as much as 25%, particularly in the south-east. The same analysis for summer (Figure 1.38 shows that despite overall summer drying, with wet days projected to become less frequent, the convection permitting model projections nevertheless suggest that when it does rain, the rainfall will be more intense.





Sub-daily and hourly precipitation rates are important drivers of flash flooding events. Figure 1.39 shows future changes in the shape of the hourly precipitation distributions from the RCM and convection permitting model. There is clear evidence of a shift to more intense hourly rainfall at the expense of lighter rainfall in all seasons, in both models, and for all ensemble members. In autumn and winter, changes in the shape of the wet value distribution are very similar between the convection permitting model and RCM. The greatest difference in changes between the models is seen in summer, where there is a much greater increase in the fractional contribution from high intensities in the convection permitting model. This is consistent with Kendon *et al.* (2014) who showed that in the convection permitting model summer convective storms are strengthened by local dynamical feedbacks.



**Figure 1.39** Future change in fractional contribution of hourly precipitation intensities to total precipitation for all seasons. Plotted is the future change in the fractional contribution of hourly precipitation events within 17 different intensity bins to total UK rainfall, for wet events only ( $>0.1\text{mm/h}$ ), in different seasons. The contributions were calculated by assigning each wet hour from every 12km UK grid box to the relevant intensity bin and multiplying the number of counts in each bin by the average intensity; these contributions are then divided by the total precipitation across all bins to give the fractional contribution. Future changes are differences between 2061-80 and 1981-2000 periods, for convection permitting model (CPM-12) (orange) and RCM-PPE (blue) members, using the RCP8.5 emissions scenario, with dark lines for the standard member.

Future changes in the percentage of dry hours (in %) are indicated in the figure legends (corresponding to standard members and ensemble-average value for CPM-12 and RCM-PPE). Intensity bin boundaries are: 0.1, 0.23, 0.41, 0.62, 0.95, 1.4, 2.2, 3.4, 5.1, 7.8, 11.9, 18.1, 27.5, 42.0, 63.9, 97.4, 148 and 500 mm/h. Reproduced from Kendon *et al.* (2019).

Overall, as Figures 1.37 to 1.39 show, there are large changes in the frequency and intensity of daily and hourly precipitation. The hydrological implications of these major shifts in precipitation characteristics for both winter and summer could be profound.

Urban flash flooding is an increasing problem as heavy, sub-daily rainfall events become more frequent. Using the convection permitting model ensemble as an event set, the frequency of precipitation exceeding 30mm/hour has been analysed for some UK cities for present-day (1981-2000) and future (2061-2080) periods with the RCP8.5 emissions scenario (Table 1.2). This methodology, which follows UNSEEN described in Section 1.4, enables more robust estimates of return times for rare events. The results show that currently the return period for such events is typically around 10 years, but the return period decreases to around 5 years by 2080.

**Table 1.2** The changing frequency of precipitation exceeding 30mm/hour for 4 cities around the UK expressed as the number of instances per year based on the 12-member ensemble with the convection permitting model. Source: Met Office

Location	Present Day (1/year)	Future (1/year)	Frequency Change
Greater London	0.095	0.139	x 1.5
Edinburgh	0.054	0.099	x 1.8
Belfast	0.136	0.233	x 1.7
Cardiff	0.092	0.191	x 2.1

### 1.5.6 Summary of Evidence of Future Changes

The new generation of Met Office models that underpin UKCP18 has generated some significant changes to the previous evidence used in CCRA2, such as increased winter rainfall and summer drying, as well as new evidence of physically plausible changes in local extremes on daily and sub-daily timescales. The framing of future climatic impact drivers in terms of changes in weather and climate regimes has been a new feature of the analysis and has emphasized the importance of model skill in representing these regimes.

The main results can be summarized as follows:

- The overall message of future winters becoming warmer and wetter still prevails. However, the changes in rainfall are likely to be more extreme than was anticipated in previous CCRA2s. The mean signal of wetter winters is a combination of more wet days, as well as an increase in the intensity of daily rainfall, which is projected to increase by as much as 25%, particularly in the



south-east. This increase in rainfall intensity potentially implies an enhanced risk of surface water flooding.

- Future winter weather may be dominated by more mobile, cyclonic weather systems, with fewer blocked winters than was the case in previous assessments. This will affect the western parts of the UK, in particular, and may contribute to more substantial increases in daily precipitation with related flooding, as well as a higher incidence of strong winds and waves. The projected shift to more mobile, cyclonic winters may also increase the risk of atmospheric river events that bring large amounts of precipitation and are major contributors to severe flooding, particularly for the mountainous regions of the UK.
- Future summers are projected to be even hotter and drier than earlier estimates. Reductions in rainfall are substantially larger over England, typically double those used in CCRA2. This can be attributed to improved simulations of summer circulation anomalies as well as higher temperatures. Despite overall summer drying, with wet days projected to become less frequent, the new kilometer-scale projections suggest that when it does rain, the rainfall will be more intense by as much as 20%.
- Better representation of the landscape and urban areas have highlighted more frequent and more severe extreme daily high temperatures and urban heat island effects. There is a very small chance of exceeding 40°C by 2040, but by 2080 on a pathway to 4°C global warming at the end of the century, the frequency of exceeding 40°C is similar to the frequency of exceeding 32°C today. Also, night-time urban heat island effects are expected to be more intense, leading to more 'tropical nights' in major cities.
- Sub-daily and hourly precipitation rates show pronounced shifts to more intense hourly rainfall at the expense of lighter rainfall, than in previous assessments. This has serious hydrological consequences including for flash flooding events.

## 1.6 An alternative view: UK climate change for specific levels of global warming

As well as assessing climatic impact drivers for specific time horizons, it can also be helpful to assess them at specific levels of global warming, e.g., 2°C above the pre-industrial state. International climate policy discussions and agreements under the UNFCCC, such as the Paris Agreement, currently frame global goals in terms of levels of global warming to be avoided. Moreover, when comparing multiple climate projections from different models with different emissions scenarios, different climate sensitivities and GHG concentrations, the use of specific time horizons can make it difficult to disentangle new evidence on climatic impact drivers from the diversity of warming rates. The use of global warming levels (GWLs) allows a systematic comparison of different sources of evidence on impacts, if the relevant climate quantities scale linearly with global mean warming, as is generally the case for many climate metrics. RCMs suggest that extreme weather metrics may also scale linearly with global mean warming, but whether this is the case for convection permitting models, and especially extreme precipitation, is still to be explored.

Rather than repeating earlier figures, this section will summarise some additional climatic impact drivers at specific global warming thresholds, based on the study by Hanlon *et al.* (2021a), and the research by Johns (2021), commissioned for CCRA3. These will focus on metrics and threshold exceedances that directly affect the natural environment, agriculture, transport, energy supply,

infrastructure and human health. The metrics and threshold exceedances are those used currently for assessing weather impacts; these have been developed by the Natural Hazard Partnership (NHP)<sup>7</sup> and form part of the National Severe Weather Warning Service (NSWWS)<sup>8</sup>. They are also part of a designated set of climate variables by the WMO Expert Team on Climate Change Detection and Indices (ETCCDI)<sup>9</sup>. The definitions of the variables shown in this section are given in Annex 2. This analysis is similar to that reported by Arnell *et al.* (2020) based on statistical downscaling of the UKCP18 global projections.

Figure 1.40 focuses on cold season impact drivers, specifically frost days, icing days and heating degree days (HDD – see Annex 2 for definition). These are documented for the current climate from the NCIC observations, and from the 21-year averages of regional model climate scenarios centred around specific global warming thresholds - 1.5°C, 2°C, 3°C and 4°C above the average for 1850-1900.

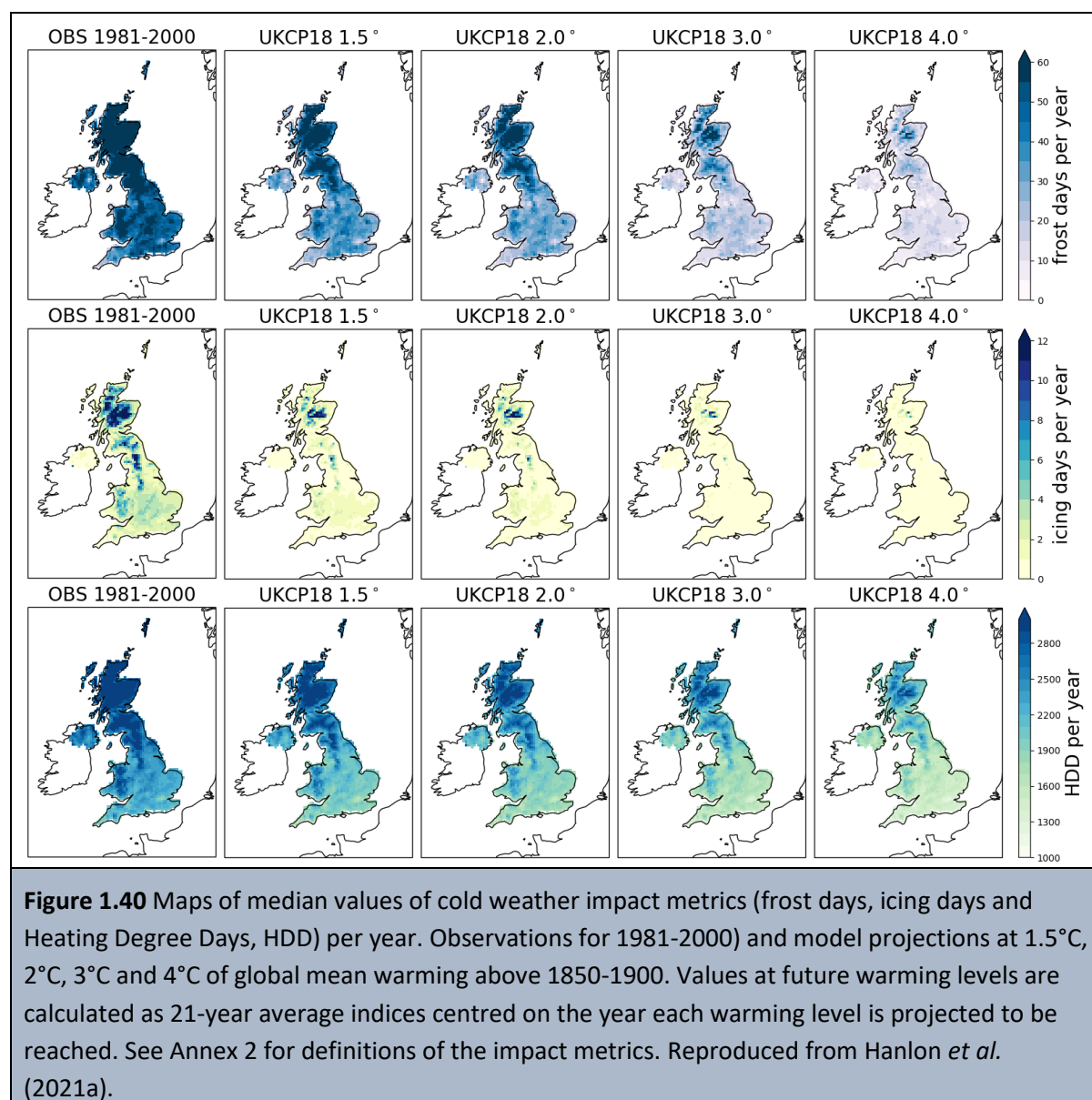
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<sup>7</sup> Natural Hazard Partnership (NHP): The NHP provides authoritative and consistent information, research and analysis on natural hazards for the development of more effective policies, communications and services for civil contingencies, governments and the responder community across the UK. It is delivered through a partnership between academia, research organisations, public sector bodies and government departments. See <http://naturalhazardspartnership.org.uk/>

<sup>8</sup> National Severe Weather Warning Service (NSWWS): The NSWWS is a service provided by the Met Office to warn the public and emergency responders of severe or hazardous weather which has the potential to cause danger to life or widespread disruption. See <https://www.metoffice.gov.uk/weather/guides/severe-weather-advice>

<sup>9</sup> WMO Expert Team on Climate Change Detection and Indices (ETCCDI): The ETCCDI has the mandate to address the need for the objective measurement and characterization of climate variability and change. The team provides international coordination and collaboration on climate change detection and the indices relevant to climate change detection, and encourages the comparison of modelled data and observations. See: <https://www.wcrp-climate.org/etccdi>





The results show firstly that there is a decline in cold weather metrics even at 1.5°C warming, compared with the observations. Second, there is very little difference in the various metrics between 1.5°C and 2°C, but there are more substantial reductions in cold season impacts at higher warming levels, with icing days almost eliminated for global warming levels of 3°C and above. Heating Degree Days (HDD)<sup>10</sup> are typically 50% lower than today at 4°C global warming.

In summer, the impact metrics revolve around higher temperatures and extended growing seasons. Figure 1.41 shows how the numbers of summer days, tropical nights, Growing Degree Days (GDD)<sup>11</sup>

<sup>10</sup> Heating Degree Days (CDD) are calculated as the product of the number of days below 15.5°C and the number of degrees below 15.5°C on each day where the temperature falls below that threshold.

<sup>11</sup> Growing Degree Days (GDD) are calculated as the product of the number of days above 5.5°C and the number of degrees above 5.5°C on each day where that threshold is exceeded.

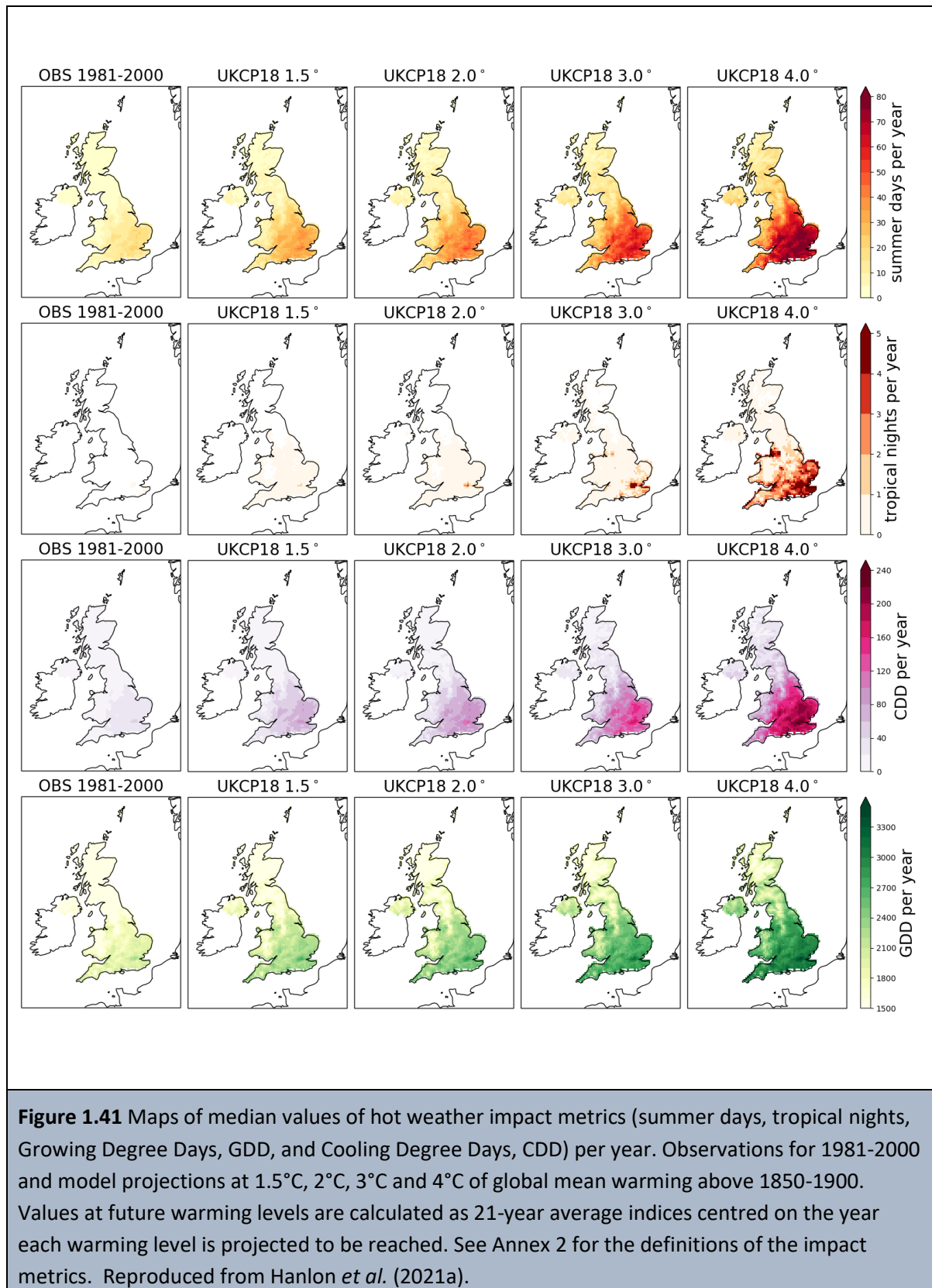
and Cooling Degree Days (CDD)<sup>12</sup> increase with global warming (see Annex 2 for definitions). Compared with cold season impacts, there is a greater difference in summer impacts between 1.5°C and 2°C global warming. There is a substantial increase in summer days as global warming increases, but outside London, tropical nights only become a serious problem at warming levels approaching 4°C and tend to be concentrated in the south-east and in urban regions around Manchester. With warmer days and nights, the number of cooling degree days increases quite rapidly even for 1.5°C and 2°C global warming, indicating the potential for increased energy demand for air conditioning.

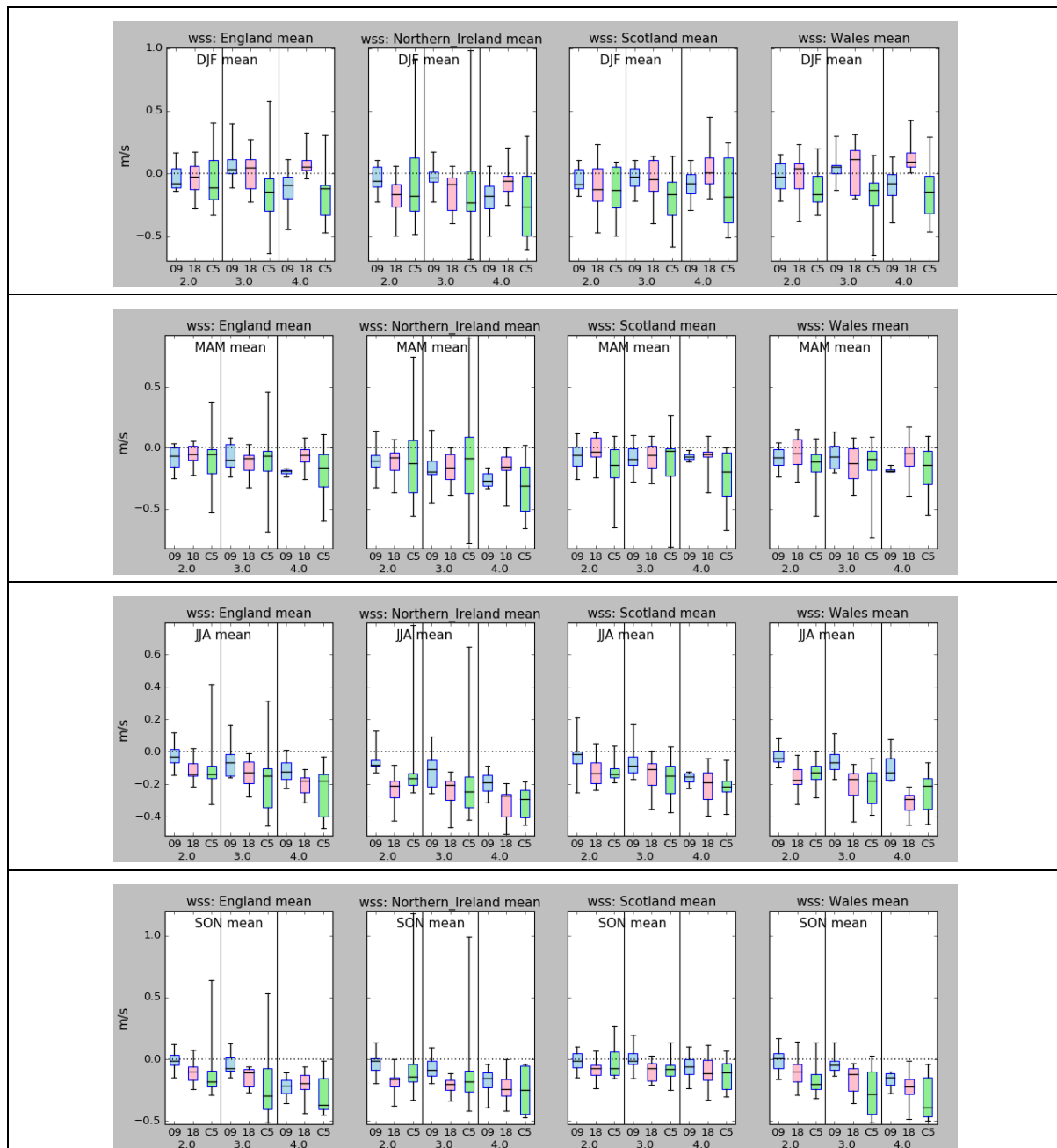
Another approach is to focus on whether the latest results from UKCP18 differ from UKCP09 in ways that are important for assessing climate risks. Johns (2021) documents a comprehensive comparison, and some specific highlights are shown here.

In the context of future renewable energy supplies, changes in near surface winds and in sunshine hours will be important climatic impact drivers, as will changes in peak demand driven for example by clustering of hot days. Figure 1.42 shows projected changes in near surface (10-metre) winds for each season and for each UK nation, from the UKCP09 regional model ensemble (blue), the UKCP18 regional model (pink) and the CMIP5 global model ensemble (green).

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<sup>12</sup> Cooling Degree Days (CDD) are calculated as the product of the number of days above 22°C and the number of degrees above 22°C on each day where that threshold is exceeded.

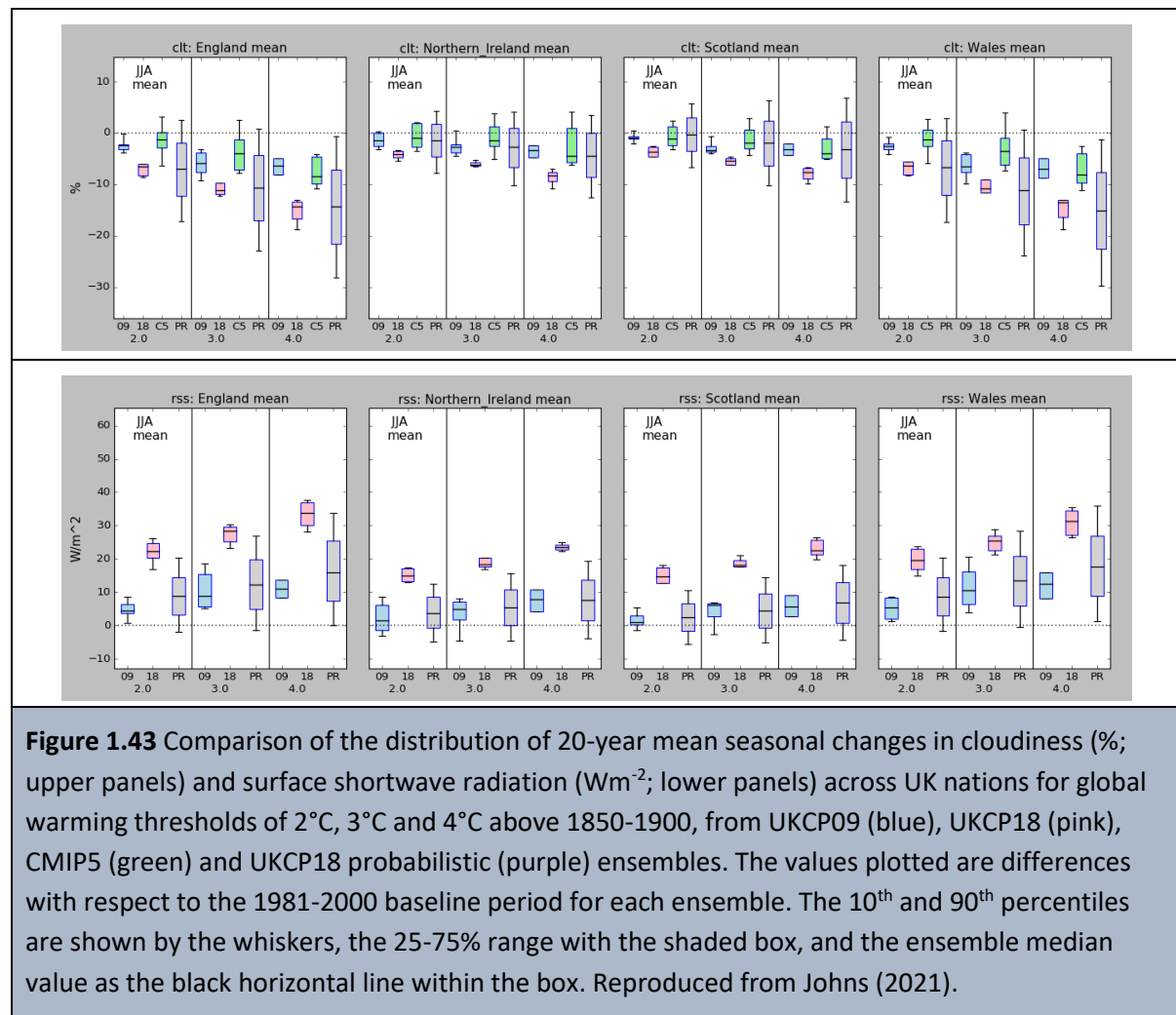




**Figure 1.42** Comparison of the distribution of 20-year mean seasonal changes in near-surface (10 meter) wind speeds (m/s) across UK nations for global warming thresholds of 2°C, 3°C and 4°C above 1850-1900, from UKCP09 (blue), UKCP18 (pink) and CMIP5 (green). The values plotted are differences with respect to the 1981-2000 baseline period for each ensemble. The 10<sup>th</sup> and 90<sup>th</sup> percentiles are shown by the whiskers, the 25-75% range with the shaded box, and the ensemble median value as the black horizontal line within the box. Reproduced from Johns (2021)

In winter, there is a large spread and no clear signal across the three sources of evidence that would imply robust changes in wind energy supply. In the other seasons there is a consistent, but small, signal of weaker winds, except in summer where the declines are larger, especially in the UKCP18 results. This is consistent with the increased prevalence of summer blocking noted earlier in Section 1.5.4.

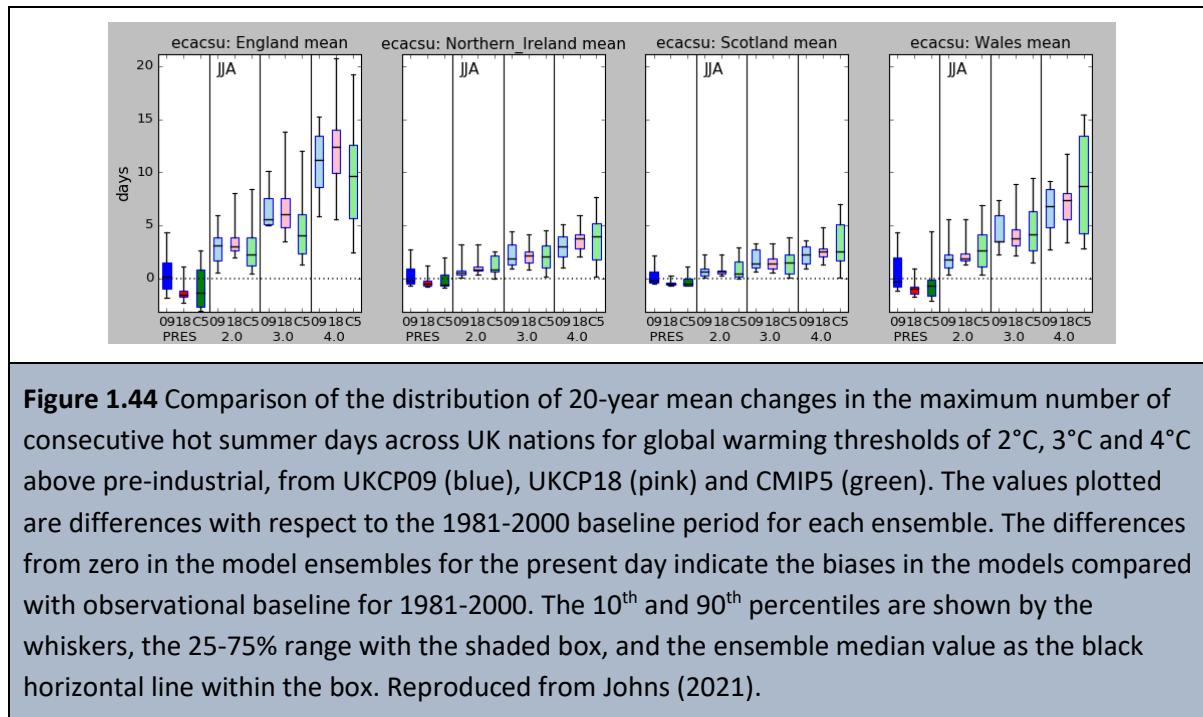
The availability of solar energy depends strongly on cloudiness and how this may be affected by changes in the UK's weather patterns. This is particularly important in summer when the availability of solar energy is at its peak. Figure 1.43 shows a comparison of projected summer changes in the cloudiness (upper panel) and surface shortwave energy (lower panel) for UK nations, from the various sources of evidence available to CCRA3. As well as the UKCP09, UKCP18 and CMIP5 ensembles, Figure 1.43 also shows the new probabilistic global projections (purple), which along with CMIP5 also include HadGEM3 results.



As in previous assessments, there is a decrease in summer cloudiness for all nations, which becomes more marked for higher warming levels. However, UKCP18 shows more substantial reductions in cloudiness for England and Wales, consistent with more dry summer blocking events, as documented in Section 1.5.4. As expected from the greater reductions in cloudiness in UKCP18, the surface shortwave radiation increases for all UK nations, increasing by as much as  $30\text{Wm}^{-2}$ .

Another aspect of electricity supply is its resilience to periods of high demand. As the UK moves to milder winters but hotter summers, some of the peak demand may occur in the summer months associated with prolonged spells of hot weather and an increased demand for air conditioning. One way to assess this risk is to consider the clustering of hot days. Figure 1.44 shows the changes in the

maximum number of consecutive hot summer days, defined as days where the maximum temperature exceeds 25°C. The length of these hot spells increases systematically for all nations as global warming levels increase. For England and Wales hot spells may increase in length by as much as 15-20 days. When these results are compared with the current duration of heatwaves (see Figure 1.10), it suggests that England and Wales may be exposed to very long spells of hot weather.



The results shown in Figures 1.42 to 1.44 may imply that earlier assessments of seasonal changes in the UK's energy needs are largely unchanged between UKCP09 and UKCP18 except for summer. UKCP18 projects that future summers could be drier and hotter, which could imply increased demand for air conditioning, especially in south-east England (see Cooling Degree Days (CDD) in Figure 1.41).

As the UK warms, drought may become an increasing risk, especially with hotter, drier summers. This has been analysed by Hanlon *et al.* (2021a) using a simple Drought Severity Index (DSI). The DSI is a rainfall-based drought index expressed in terms of the n-month accumulated precipitation deficit as a percentage of the mean annual rainfall of the location. The DSI has been computed for 3-month, 6-month, 12-month and 36-month periods in order to cover timescales relevant to meteorological, agricultural and hydrological droughts. Meteorological droughts are defined essentially on the basis of short-term rainfall deficiencies, whereas agricultural droughts relate to the gradual depletion of soil water during the growing season, and hydrological droughts are accumulated shortfalls in runoff or aquifer charge over longer periods.

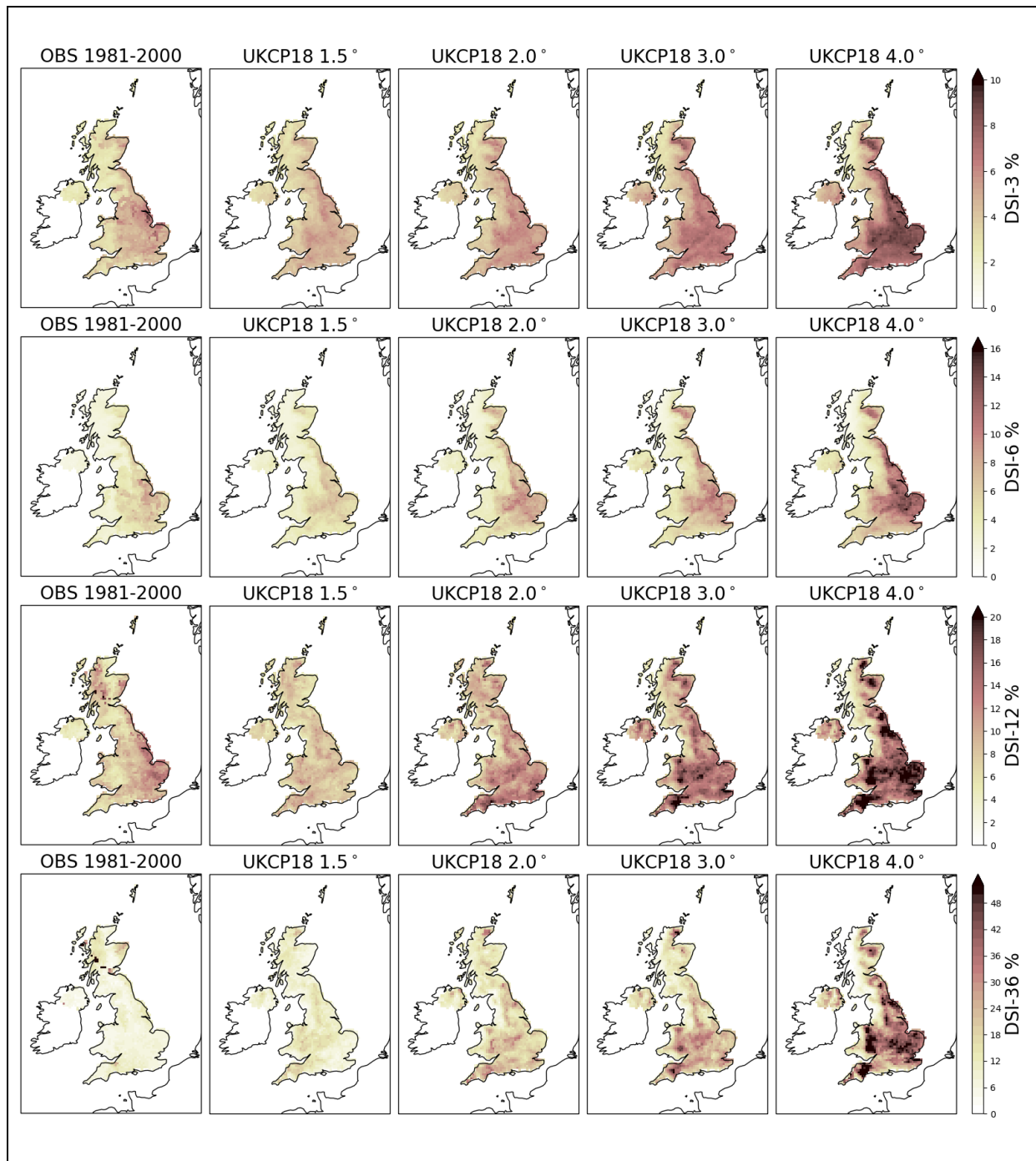
Figure 1.45 shows the DSI for a range of durations from 3 to 36 months across various global warming thresholds, where the drought severity is expressed as the % shortfall in the n-month accumulated precipitation with respect to the climatological annual average for the specific global warming level. The results show that essentially for all drought periods, their severity increases with

the warming level. This is particularly the case for the longer period, hydrological droughts where the changes in the accumulated deficits can be substantial. This would imply severe pressures on water resources and the sustainability of agriculture.

In summary, this additional analysis, using the framework of global warming levels rather than time horizons, has demonstrated how climatic impact drivers, directly relevant to specific sectors, are likely to change. It has also highlighted where there are significant differences in the evidence base given by UKCP18 from that used in earlier CCRA's. Key points include:

- All parts of the UK will continue to experience a steady reduction in frost days as global warming increases, implying a general trend towards fewer cold weather-related impacts in the long-term average, although some years will still see similar numbers of frost days and cold-related impacts as in recent years.
- A significant reduction in the number of icing days across the UK with increases in global warming, with fewer severe cold weather impacts and potentially less transport disruption. Most of the reductions in icing days occur up to a global warming of 3°C with little further reduction from 3 to 4°C.
- An increase in the incidence of high summer daytime temperatures throughout the UK. In the future, Scotland and Northern Ireland could start to see high summer temperatures similar to those of England and Wales currently.
- A rapid rise in the frequency of 'summer days' and 'tropical nights'. Since most of these events will cluster during the summer months, adaptation to cope with far hotter summers than we are currently experiencing will become important, with cities, especially London, facing the greatest challenge.
- A reduction in heating degree days and an increase in cooling degree days is projected for all global warming levels. Over South East England, cooling degree days increase 6-fold for a global warming of 4°C
- A clear signal in UKCP18 of decreasing total cloud amount and increasing surface shortwave radiation in summer, especially in southern England, is likely associated with more positive SNAO summers and associated reductions in rainfall and cloudiness. There are also more significant reductions in summer near-surface winds in UKCP18. On the other hand, there is no consistent signal for reductions in windiness in winter.
- Meteorological, agricultural and hydrological droughts are expected to become more severe with implications for water resource management.





**Figure 1.45** Maps of median values of the Drought Severity Index (DSI) computed for 3 (DSI-3), 6 (DSI-6), 12 (DSI-12) and 36 (DSI-36) month periods. The DSI is the n-month accumulated shortfall expressed as a % of the annual average precipitation. Observations for 1981-2000 and the model projections at 1.5°C, 2°C and 4°C of global mean warming above 1850-1900. Values at future warming levels are calculated as the 21-year average indices centred on the year each warming level is projected to be reached. Reproduced from Hanlon *et al.* (2021a).



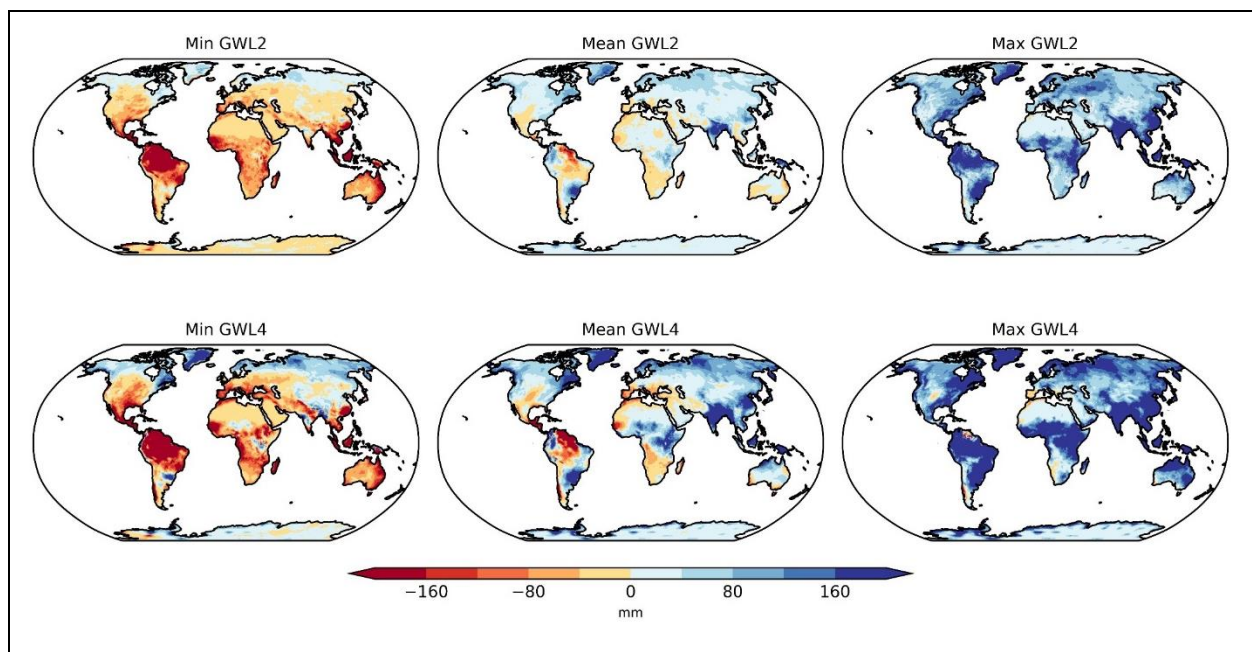
## 1.7 Projected climate changes worldwide

The UK is sensitive to climate change beyond its borders and so global projections are helpful for thinking about the international dimensions of climate risk to the UK (such as disrupted food supply chains). Extensive information on projected global patterns of climate change is presented in IPCC Assessment Reports and Special Reports (see <https://www.ipcc.ch>). While these include comprehensive assessments of uncertainties in regional climate changes, these are typically presented in terms of the average changes from multiple models, along with information on the degree of consensus between models.

For risk assessments, however, it can be useful to provide clear information on ranges of projected changes, hence the presentation style adopted in the UKCP09 and UKCP18 probabilistic projections for the UK (Murphy *et al.*, 2009; Murphy *et al.*, 2018). This can be particularly important for projected changes in precipitation, which can often differ in sign between models or realisations. Since the average change can be substantially smaller in magnitude than for individual realisations, this can fail to provide adequate information on the risk of larger potential changes.

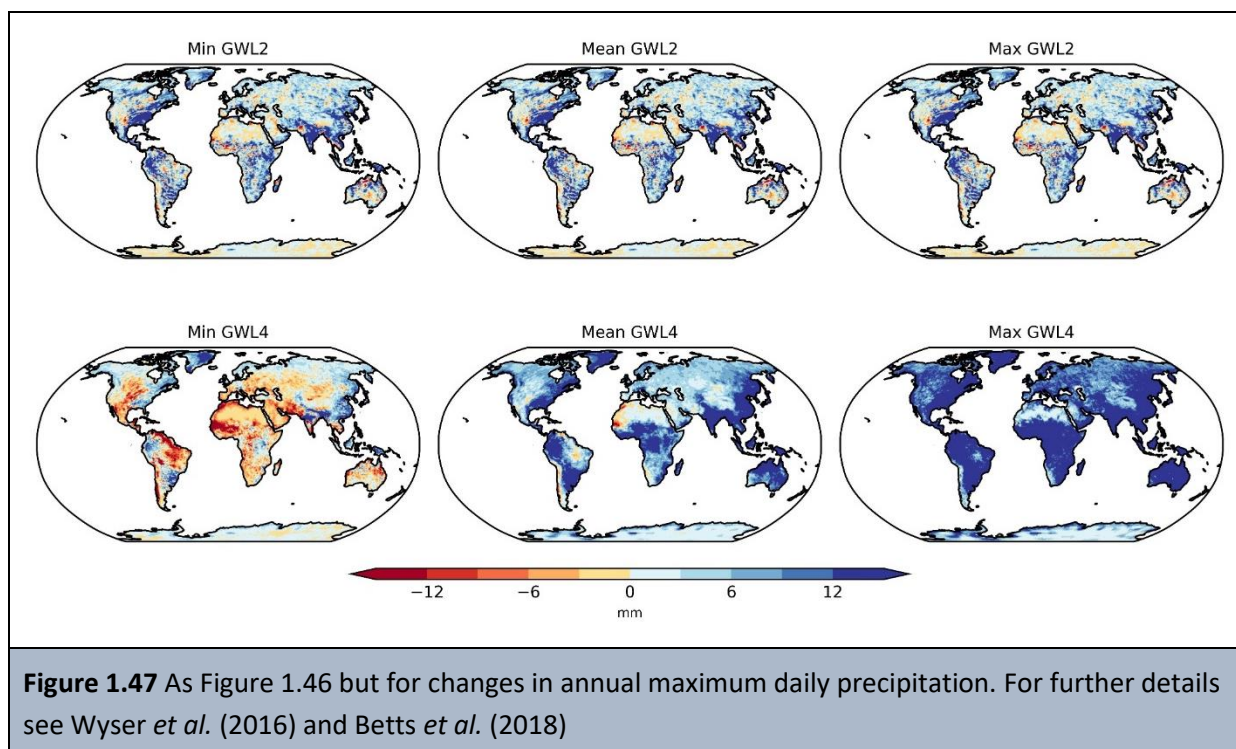
Here, projected global patterns of future changes in selected indices of precipitation are presented from an ensemble based on two different atmosphere models driven by sea surface temperatures from a selection of CMIP5 models, to illustrate the altered character of worldwide precipitation at 2°C and 4°C global warming, showing ranges of outcomes following the style of UKCP09 and UKCP18.

Annual total precipitation is projected to change in all land regions of the world (Figure 1.46). In this ensemble, increased precipitation across the Arctic region is consistently projected by all members at both GWLs. In all other regions, there is no consensus on the sign of the change across the range of outcomes from the driest to the wettest at both GWLs. However, the pattern of changes stays largely the same across GWLs and the magnitude of the changes is generally larger at 4°C global warming compared to 2°C.



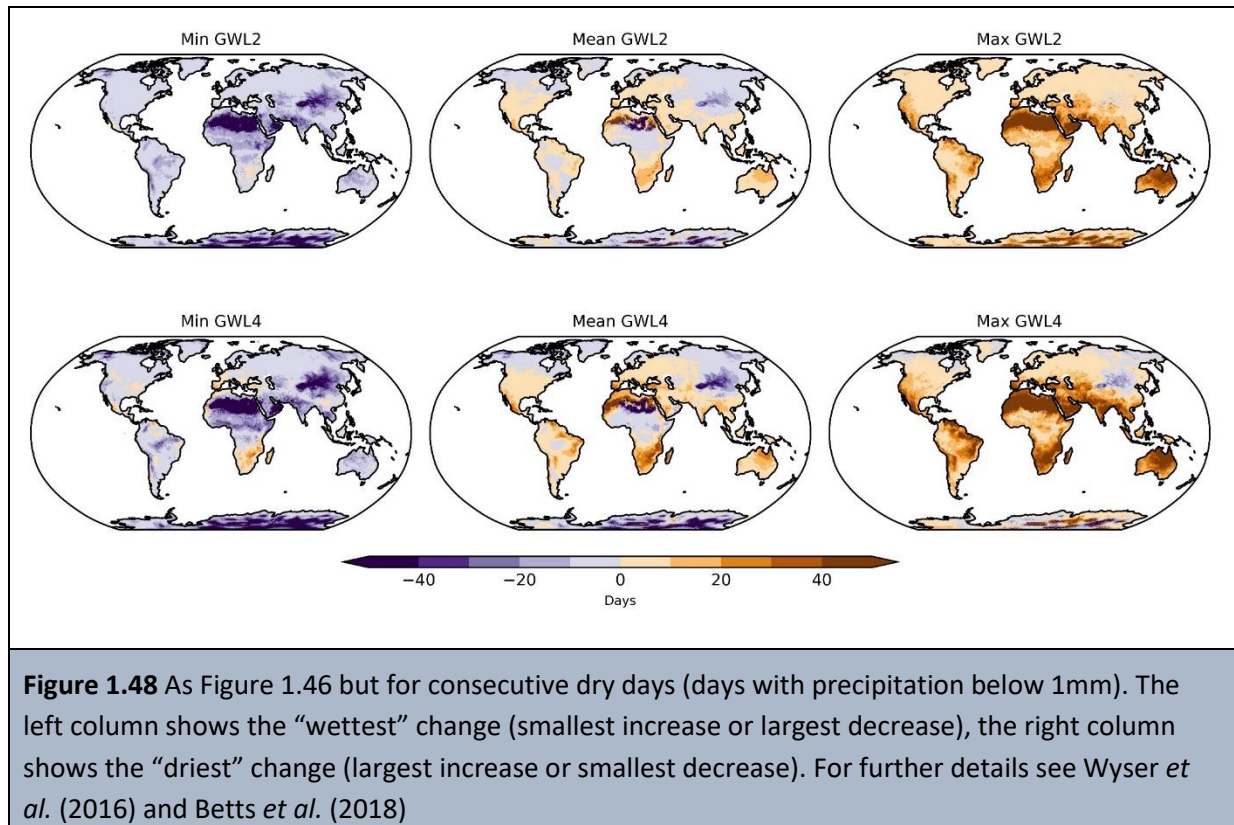
**Figure 1.46** Projected changes in 20-year mean annual total precipitation (mm) relative to 1981-2010, at global warming levels (GWLs) of 2°C (top row) and 4°C (bottom row) relative to preindustrial, from an ensemble of simulations with the atmosphere components of the HadGEM3-GC2 and EC-Earth vn3.1 climate models; these are driven by patterns of sea surface temperature change from a subset of the CMIP5 projections using the RCP8.5 concentration pathway. The centre column shows the multi-model mean for each grid point, the left column shows the “driest” change (largest decrease or smallest increase) at each grid point, and the right column shows the “wettest” change (smallest decrease or largest increase). For further details see Wyser *et al.* (2016) and Betts *et al.* (2018)

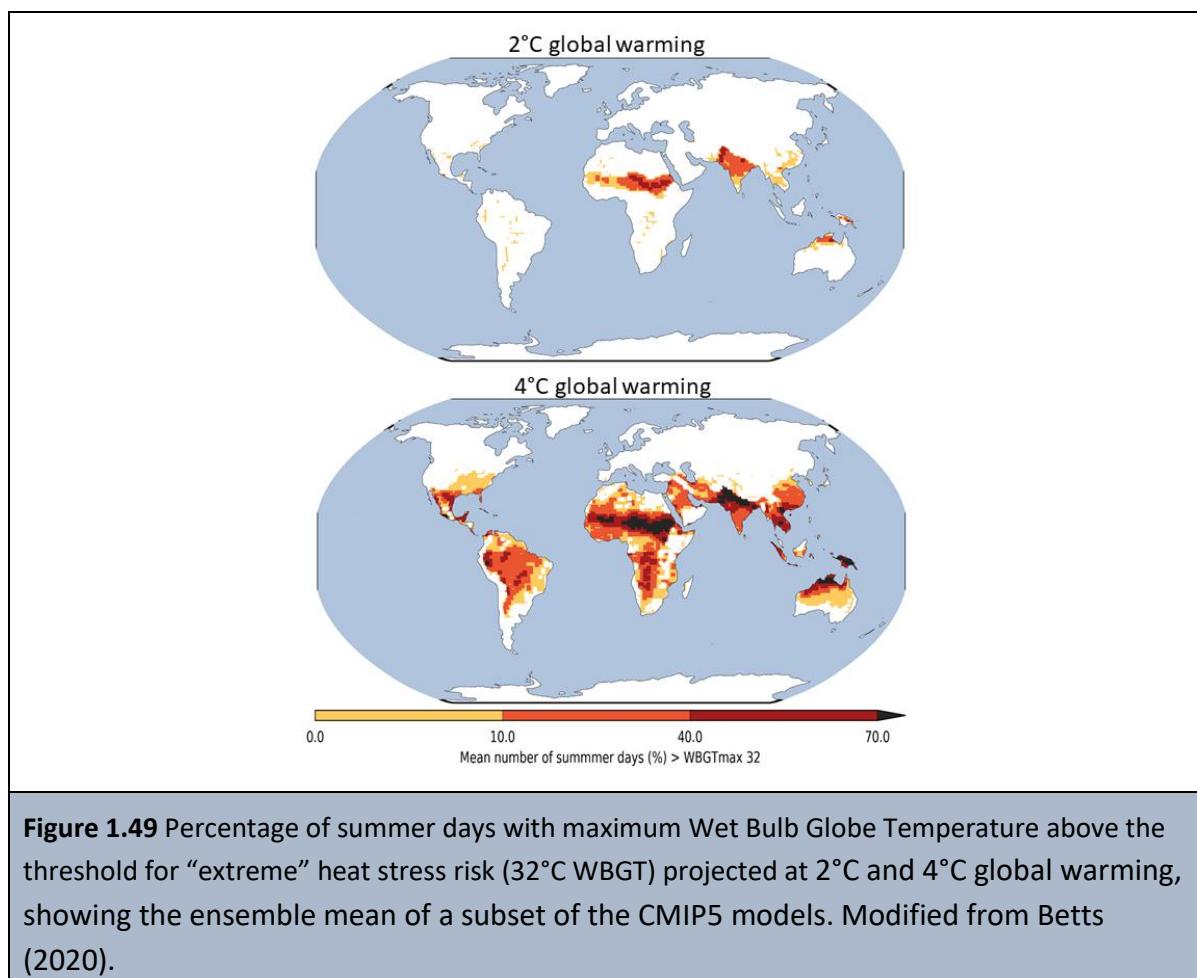
Heavy precipitation shows a more consistent increase at 2°C global warming, but uncertainty in the sign of change becomes more widespread at 4°C warming (Figure 1.47). Importantly, the largest projected increases are generally substantially larger than the mean of the projections, underlining the importance of considering the range of projected changes for risk assessments.



The length of dry spells is also projected to change in different ways in different regions worldwide, again with disagreements in the direction of change among the ensemble in many regions (Figure 1.48). At 4°C global warming, there is a consensus across all models on dry spells increasing by 10 days or more across large parts of southern Africa, the Iberian Peninsula and a number of small regions, and a consensus on shorter dry spells in eastern central Asia and some Arctic lands, but in most regions the ensemble projects that dry spells could either increase or decrease. In some regions, including highly populated areas such as the Indian subcontinent, the maximum projected 20-year mean increase is over 40 days per year.

The most extreme high temperatures are projected to occur in regions that are already hot. Human heat stress depend on humidity as well as temperature, and for industry uses is routinely quantified with Wet Bulb Globe Temperature (WBGT) using temperature, humidity and solar radiation. WBGT of 32°C is classified as “extreme risk” of heat stress and is rarely seen in the current global climate. Figure 1.49 shows the percentage of summer days with maximum WBGT above 32°C projected for GWLs of 2°C and 4°C, using the mean of several simulations with a subset of the CMIP5 models. Extreme heat stress conditions are projected for more than 10% of summer days in most tropical regions and many parts of the sub-tropics at 4°C global warming, and many of the more highly-populated areas of the world for more than 40% of summer days.



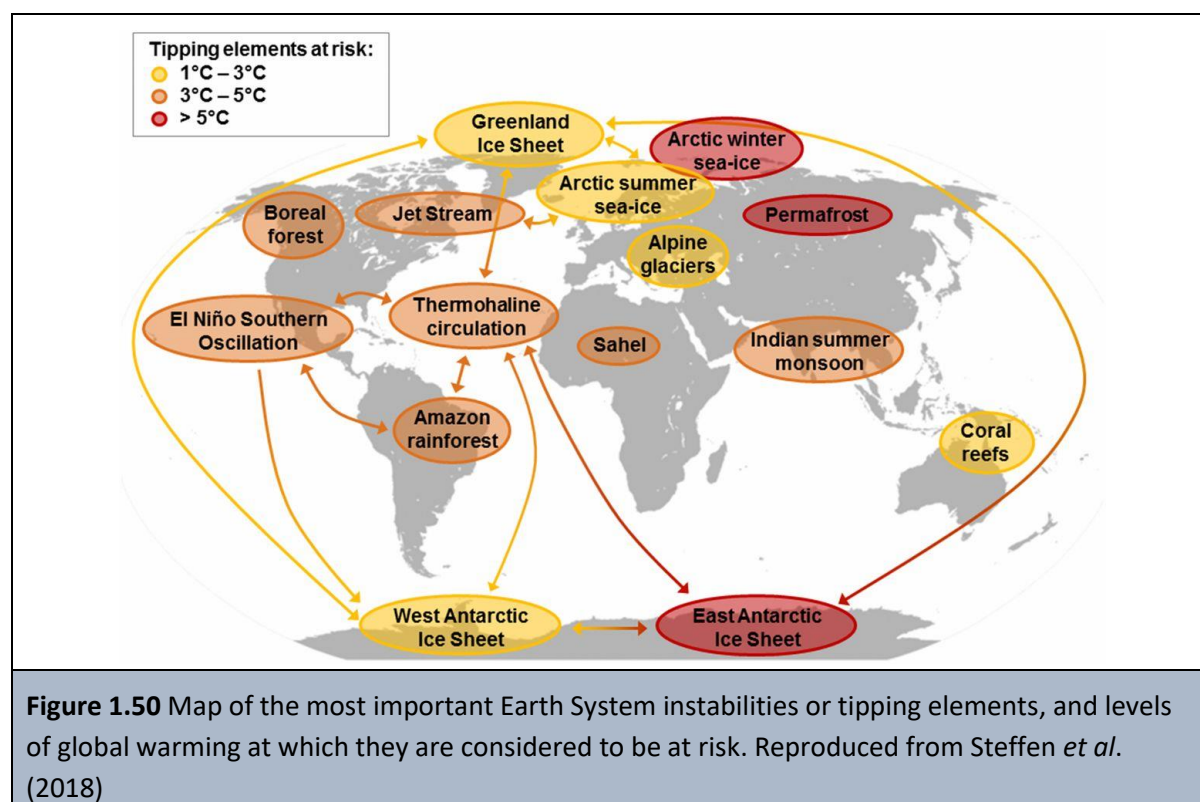


## 1.8 Earth System Instabilities – Potential risks of rapid and/or irreversible changes

Earth System Instabilities (often known as tipping points) describe accelerating, rapid or irreversible changes within the Earth System in response to external forcing. These can involve the physical climate system (e.g. ice sheets), terrestrial carbon cycles and ocean biogeochemistry, they can operate on a range of timescales and can be manifest at global or regional levels. Some are regarded as reversible, but some may persist for centuries or longer. Recent work (e.g. Steffen *et al.*, 2018) has emphasised the links between various Earth System instabilities and considered the risk that self-reinforcing feedbacks, often referred to as tipping cascades, could push the Earth System toward a planetary threshold that, if crossed, could prevent stabilization of the climate at intermediate temperature rises even as human emissions are reduced.

Figure 1.50 provides a useful summary of our current understanding of potential candidates that may exhibit behaviours that could drive the system to more extreme climate states. A report on ‘Effect of Potential Climate Tipping Points on UK Impacts’ has been produced for CCRA3 (Hanlon *et al.*, 2021b).





For the purposes of CCRA3, three classes of Earth system instabilities are considered. Firstly, those that could affect the UK directly through changes in our regional weather and climate without necessarily changing the level of global warming. Secondly, those involving changes in land ice, affecting sea level rise impacts in the UK and worldwide. Thirdly, those related to feedbacks involving carbon or other biogeochemical cycles that could increase the likelihood of higher levels of global radiative forcing, and hence increase the likelihood of large regional climate changes in the UK.

### 1.8.1 Weakening or collapse of the Atlantic Meridional Overturning Circulation

The UK's weather and climate are fundamentally controlled by the Atlantic Meridional Overturning Circulation (AMOC), and especially by the warm, returning branch, the Gulf Stream. Although shutdown of the AMOC is considered very unlikely this century, it remains a plausible outcome in the next century (IPCC, 2019). However, significant weakening of the AMOC is considered likely and the latest results (Weijer *et al.*, 2020) suggest that the CMIP6 models project stronger weakening than in IPCC AR5, with a possible AMOC decline between 34% and 45% by 2100. These projected declines are already represented in the UKCP18 results.

Weakening of the AMOC would lead to a cooling effect on the UK's climate, although not enough to offset anthropogenic warming. However, the effects of AMOC weakening on specific aspects of the UK's weather and climate may act to exacerbate the trends due to global warming documented in Section 1.5. These include shifts in rainfall patterns (including summer drying), increases in winter

storminess, and further rises in sea level due to changes in the ocean density and circulation (e.g., Vellinga and Wood, 2008).

Ritchie *et al.* (2020) have considered the impacts on UK land use and food production of an extreme scenario in which there is a rapid weakening and AMOC collapse between 2030 and 2050. Figure 1.51 shows the changes in temperature and precipitation through the 21<sup>st</sup> century, without and with AMOC collapse, where the climate change signal is taken from UKCP09 regional model projections using the SRES-A1B emission scenario (Nakićenović, N. *et al.*, 2000).

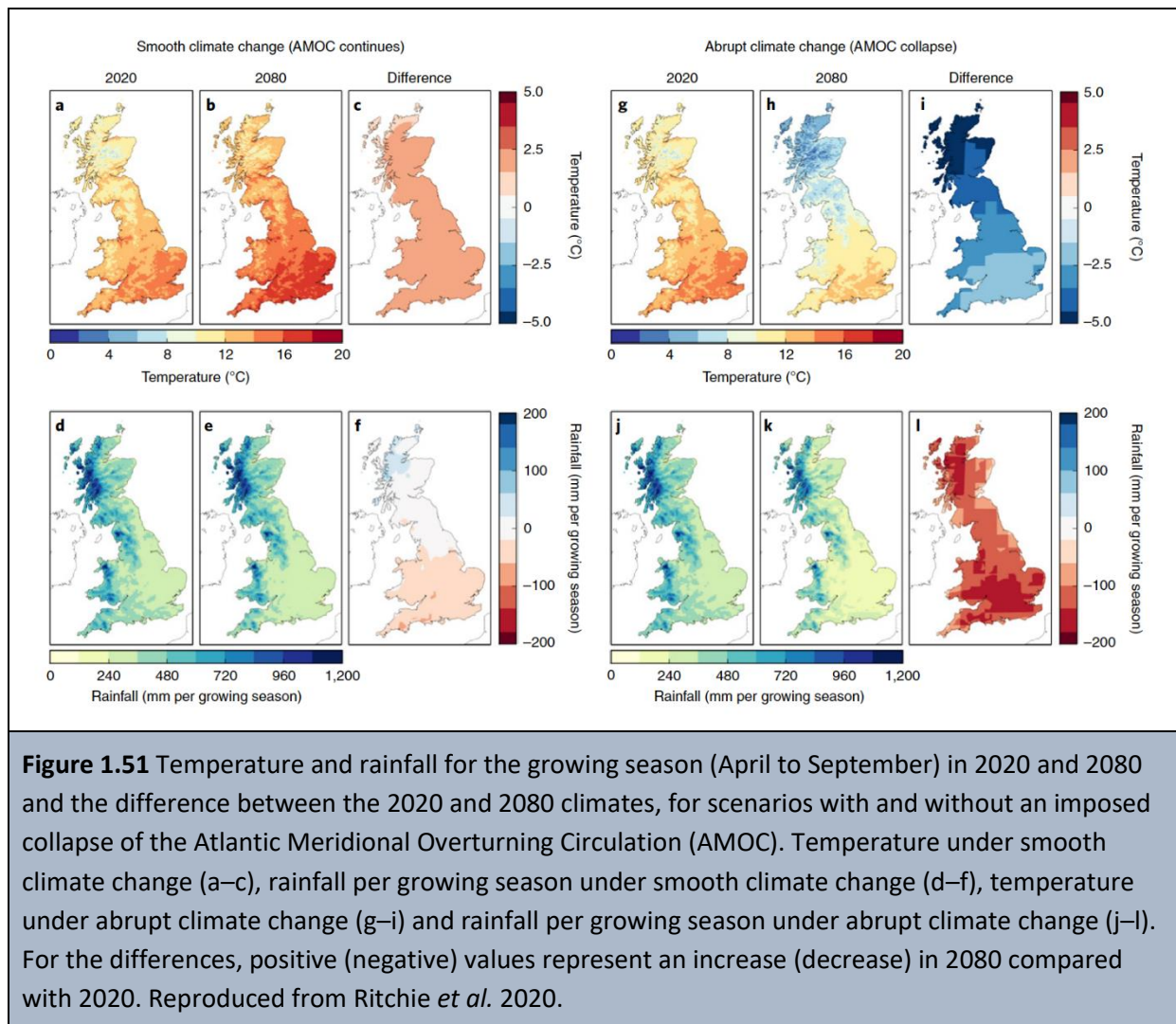


Figure 1.51 provides a striking demonstration of the impacts of AMOC collapse on growing season conditions in the context of ongoing climate change. The impacts are likely to include widespread cessation of arable farming, with losses of agricultural output that are an order of magnitude larger than the impacts of climate change without an AMOC collapse.

### 1.8.2 Changes in the behaviour of the North Atlantic Jet Stream

As already discussed, the UK's weather and climate are strongly influenced by the position and strength of the North Atlantic jet stream which in turn can alter the frequency and/or magnitude of high-impact or extreme weather events. Recent extreme events, involving winter flooding and summer heatwaves, have led to questions around whether the behaviour of the jet stream is changing, with more instances of major meanders north and south, and more stalling of these meanders. Meanders in the jet are often referred to as Rossby or planetary waves and we know that slow moving, amplified Rossby waves favour the occurrence of extreme weather conditions over the UK. For example, extended periods of wet or dry weather, such as winter 2013/14 and spring 2020, correspond to a jetstream meander stalling and becoming locked in one position.

It has been postulated that the amplified warming of the Arctic with the associated loss of Arctic sea ice may be weakening the jet stream and hence making it more susceptible to amplified and persistent wave anomalies (e.g., Francis and Vavrus, 2012). However, evidence to support this hypothesis has not yet been forthcoming, but it has raised interesting questions over how the jet stream might respond to warming. We know that there is a link between the strength of the jet stream and its meanders north and south (e.g., Woollings *et al.*, 2018), in which a weaker jet stream favours more meanders, and, relatedly, more blocking events and accompanying high-impact weather. However, Woollings *et al.* (2018) have shown that North Atlantic jet variability is modulated on multi-decadal time scales, with decades of a strong, steady jet being interspersed with decades of a weak, variable jet.

There is as yet no robust evidence that the North Atlantic Jet Stream is changing. Furthermore, the future behaviour of the North Atlantic Jet stream is not understood, and yet could have profound implications for the UK's weather and climate. The potential exists for significant changes in its preferred location, in its variability and in its propensity for slow moving, or even stationary, amplified Rossby waves. There is an urgent need to fill this knowledge gap.

### 1.8.3 Accelerated loss of Antarctic and Greenland ice sheets

Sea level rise has two major contributors – thermal expansion of the oceans as they warm (remembering that the oceans take up around 90% of the additional energy trapped in the planet), and the accumulation of ocean water mass as ice sheets and glaciers melt. Today mass accumulation dominates global sea level rise accounting for about two-thirds of the total. This is primarily due to accelerating loss of mass from the major ice sheets of Greenland and Antarctica.

The main mechanism for Greenland ice melt is changes in surface mass balance, where ice melts faster than snow can accumulate. This mechanism occurs at a steady rate and is not likely to exhibit accelerating or abrupt changes. The IPCC SROCC (2019) estimates that the complete loss of Greenland ice would contribute around 7m to global sea level rise, but this would take more than 1000 years. Sea level rise due to Greenland ice melt during the 21st century would be closer to 10s of centimetres.

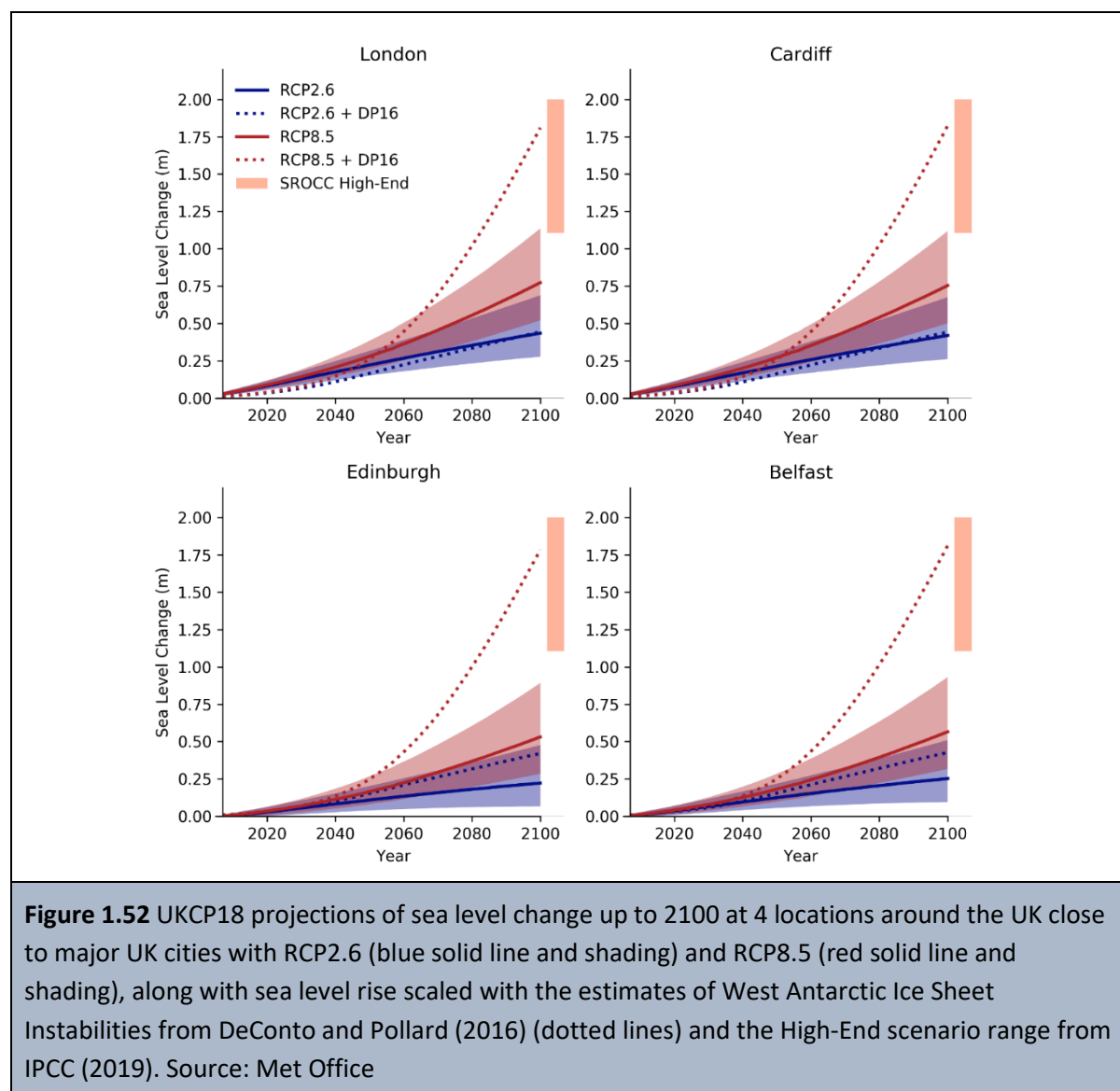
The main risk of abrupt change comes from West Antarctica, which is losing ice mass primarily due to ice flow processes but could start losing ice more rapidly from accelerating instability processes.

Recent advances have highlighted the potential for collapse of the West Antarctic Ice Sheet and consequent acceleration in the rate of global sea level rise. This is a predominantly marine-based ice sheet, where ice mass input to the ocean is governed primarily by ice flow processes rather than the surface mass balance that dominates for the East Antarctic Ice Sheet.

There are indications that collapse of the West Antarctic Ice Sheet could already be underway, through a positive feedback known as 'Marine Ice Sheet Instability' in which the ice sheet separates from its grounding line and floats free where it can melt more rapidly (e.g., Rignot *et al.*, 2014). Recently, a second potential positive feedback on ice loss from West Antarctica has been proposed called 'Marine Ice Cliff Instability' (Pollard *et al.*, 2015). This feedback would be triggered by disintegration of the floating ice shelves around Antarctica; wherever these leave behind tall coastal ice cliffs that would be structurally unstable, they may collapse entirely leaving behind further unstable cliffs. This could lead to self-sustaining ice losses and associated global sea level rise of order 1m by 2100 if the feedback were rapid and widespread (e.g. DeConto and Pollard, 2016).

Figure 1.52 shows the impact of Marine Ice Cliff Instability on sea level rise for selected UK cities based on the simulations of DeConto and Pollard (2016) compared with the UKCP18 projections (Palmer *et al.*, 2018), along with the high-end assessments from IPCC (2019). These assessments show that the UK should be prepared for up to 2m sea level rise by 2100 in the event of accelerated Antarctic melting, which suggests a similar upper bound to the UKCP09 H++ scenario (1.9m) for the UK.





### 1.8.4 Permafrost thawing and additional carbon emissions

Permafrost is a mixture of soil, rocks and ice which remains permanently frozen throughout the year. Carbon stored in the permafrost is relatively inert as temperatures are too cold for much microbial activity to occur. A warming climate can induce environmental changes that accelerate the microbial breakdown of organic carbon and the release of the greenhouse gases, carbon dioxide and methane. Methane is of particular concern because although its lifetime is much shorter, it is a far more potent greenhouse gas than carbon dioxide. The addition of these greenhouse gases to the atmosphere would increase global warming and lead to further thaw, an amplifying process referred to as the “permafrost carbon feedback”.

Should the permafrost thaw, the carbon would not necessarily be released into the atmosphere immediately. The timescales of soil carbon decomposition are much slower than the projected rate of permafrost thaw. In addition, there is likely to be enhanced vegetation growth caused by warmer

temperatures with increased CO<sub>2</sub> uptake. Schuur *et al.* (2015) estimate that for a high emission scenario, carbon release from permafrost is projected to be in the range 37–174 Pg of carbon by 2100, which gives a possible range of additional global warming of 0.13–0.27°C by 2100 and up to 0.42°C by 2300.

However, recent research has highlighted the importance of abrupt thawing events that could release far more carbon than a gradual thawing assessed so far (Turetsky *et al.*, 2020). Across the Arctic and Boreal regions, permafrost is collapsing suddenly as pockets of ice within it melt. Instead of a few centimetres of soil thawing each year, several metres of soil can become destabilized within days or weeks. The land can sink and be inundated by swelling lakes and wetlands.

Abrupt thaw would probably occur in up to 20% of the permafrost zone (Olefeldt *et al.*, 2016) but could contribute half of permafrost carbon through collapsing ground, rapid erosion and landslides. Under a high emission scenario Turetsky *et al.* (2020) estimate that emissions across 2.5 million km<sup>2</sup> of abrupt thaw could provide a similar climate feedback as gradual thaw emissions from the entire 18 million km<sup>2</sup> permafrost region. After considering abrupt thaw stabilization, lake drainage and soil carbon uptake by vegetation regrowth, they conclude that models considering only gradual permafrost thaw are substantially underestimating carbon emissions from thawing permafrost.

The impact of permafrost thaw on the UK would be an indirect one, associated with more rapid global warming and subsequent changes to our weather and climate. Also, the release of additional greenhouse gases would reduce the allowable carbon budget to keep within a certain level of global warming and hence is important for mitigation policies. For example, Gasser *et al.* (2018) compared the carbon budgets and targets of the Paris Agreement with carbon emissions from permafrost in an Earth system model. They concluded that permafrost thaw could use up 10-100% of the allowable carbon budget to stay within 1.5° C and up to 25% of the budget to stay within 2°C. Once emitted these additional carbon emissions would be irreversible for centuries.

### 1.8.5 Reduced carbon uptake by the biosphere

Land and ocean ecosystems act as natural buffers that limit the increase of CO<sub>2</sub> in the atmosphere by absorbing and sequestering nearly half of emitted CO<sub>2</sub>. As human emissions have continued to increase, this natural climate change mitigation has so far proportionally kept pace with emissions, with, for example, enhanced vegetation growth from CO<sub>2</sub> fertilisation.

It is expected that the ocean's ability to take up carbon will continue, although the oceans will become more acidic with consequences for marine organisms (IPCC, 2019). This may not be the case for the land carbon sink where the situation could deteriorate quite rapidly, as deforestation and changing climatic conditions affect the major forests of Amazonia and the northern hemisphere boreal regions.

The Amazon rainforest involves a symbiotic relationship between the trees and the hydrological cycle in which a significant fraction of the rainfall falling on the forest is recycled by the forest in a self-sustaining feedback loop. In recent decades, new forcing factors – deforestation, widespread use of fire to clear vegetation and climate change - have begun to break that loop. There is also evidence that the recent climate of Amazonia has been subject to large oscillations between severe droughts and floods (Yang *et al.*, 2018) that act to destabilise the forest system. The severity of the

droughts is part of an emerging picture of an increasingly extended dry season, potentially associated with the warming of the tropical North Atlantic and shifting circulation patterns, but also with deforestation.

All these factors have raised the question of how much would be required to degrade the symbiotic relationship between the forest and the hydrological cycle, to the point that Amazonia is unable to support rain forest ecosystems and lose its role as a robust and important sink of carbon. Lovejoy and Nobre (2018, 2019) have suggested that the negative synergies between deforestation, climate change and the widespread use of fire indicate a tipping point for the Amazon system at 20-25% deforestation. Current estimates of deforestation are around 17% for the whole of Amazonia so the forest system is already close to that suggested tipping point. The loss of forest would lead to substantial losses of biodiversity and carbon with far-reaching ramifications.

The boreal forests of the northern hemisphere are also at risk from climate change. These forests store 30-40% of all land-based carbon in the world, and most of that carbon is found in the soils. High latitude warming is projected to increase dieback and disturbance in boreal forests, with increased prevalence of fires, pests and disease. All these factors could alter the structure, composition and functioning of the boreal forest systems. However, the impact on the climate system is expected to be less profound than for the Amazon rainforest, where most of the carbon is stored in the trees, and deforestation and climate change may lead to an abrupt collapse of the ecosystem.

Regarding UK impacts, the effects of forest loss would be indirect. The loss of forests would reduce the efficiency of terrestrial carbon sinks, leading to increased atmospheric concentrations and accelerated global warming. As with permafrost thaw, allowable carbon budgets to stay within specific levels of warming will be reduced with implications for mitigation.

## 1.9 Looking ahead to CCRA4

Important advances in climate science evidence have been made leading up to CCRA3 and during its production, particularly through UKCP18 and subsequent releases of further components of the UK Climate Projections. However, in many cases, the full range of evidence, especially from the regional and convection-permitting models, became available while the CCRA3 process was underway and hence in many cases could only be exploited in a limited way in the sectoral risk assessments. This is reflected in the assignment of confidence levels. One example is the use of threshold exceedance metrics with the convection-permitting model: information on these metrics is provided in Annex 2 for potential further use in research to inform CCRA4. Moreover, significant knowledge gaps still exist: key examples are summarised here, with suggestions for further research and development leading up to CCRA4.

### 1.9.1 Knowledge gaps in the scientific evidence

A theme of this chapter has been the importance of considering the volatility of the UK's weather and climate and how this may change in the future. Although some basic analysis has been done there needs to be a much greater emphasis on this in the future.

Weather regime analysis is one way forward (e.g. Neal *et al.*, 2016) which is already proving very valuable in operational forecasting and has been explored by De Luca *et al.* (2019) for interpreting future climate change in the CMIP5 projections. This needs to be repeated with the latest generation of models used in UKCP18 and IPCC AR6. Regime analysis has also been exploited for interpreting the incidence of extreme events which show clear evidence for preferred patterns (e.g. Darwish *et al.*, 2020).

Using weather regimes, insightful diagnostics on frequencies, residence times and transitions can be explored for the current climate and the links with modes of climate variability can be produced. These would form the basis for exploring how the UK's weather regimes may evolve with global warming and with changes in modes of climate variability. Regime analysis is already used very effectively in weather forecasting for identifying forthcoming risks across a range of sectors and this expertise may therefore be useful for assessing future levels of risk under climate change. Weather regimes may also act as useful vehicles for climate risk communication.

Linked to this, there needs to be a major focus on understanding the behaviour of the North Atlantic Jet Stream and how this will evolve in the future. This is vital for addressing current and future changes in storminess, atmospheric rivers, extreme winds, waves and coastal surges. As discussed in Section 1.8.2, this is a fundamental knowledge gap which needs to be filled before CCRA4.

### 1.9.2 Storylines and Scenarios

The conventional approach to representing uncertainty is through probabilistic approaches, based on ensembles of climate model simulations. One consequence of this is that the low-likelihood, high-impact events that may pose the greatest risks are difficult to isolate and factor into a risk assessment. An alternative approach is emerging called event-based storylines. Event-based storylines are physically self-consistent unfoldings of past events, or of plausible future events, with an emphasis on plausibility rather than probability (Shepherd *et al.*, 2018). This concept links directly to common practice in disaster risk management using “stress-testing” for emergency preparedness based on events that are conditional on specific (plausible) assumptions about the hazards and possible aspects of exposure and vulnerability of the affected human or ecological system. They are particularly applicable to extreme or unprecedented events whose probability cannot be quantified, but whose impacts could be profound.

There are several reasons why storylines may complement current, probabilistic-based methods:

- (i) Improving risk awareness by framing risk in an event-oriented rather than a probabilistic manner, which corresponds more directly to how people perceive and respond to risk.
- (ii) Strengthening decision-making by allowing one to work backwards from a particular vulnerability or decision point, combining climate change information with other relevant factors to address compound risk and develop appropriate stress tests.
- (iii) Emphasizing the plausibility rather than probability. This concept links directly to common practices in disaster risk management using “stress-testing” for emergency preparedness based on events that are conditional on specific, but plausible assumptions.

- (iv) Exploring the boundaries of plausibility, thereby guarding against false precision and surprise. Storylines also offer a powerful way of linking physical with human aspects of climate change.
- (v) Exploiting the latest generation of kilometre-scale climate models where the ensemble size may not be sufficient to define probabilities, but where the physical realism is such that plausible, and potentially unprecedented, extremes can be captured.

When co-developed by climate scientists and stakeholders, event-based storylines can provide a useful way of communicating and assessing climate-related risk in a specific decision-making context. Event-based storylines allow for conditional explanations, without full attribution of every causal factor, which is crucial when some aspects of the latter are complex and highly uncertain.

Strategic planning in government and business routinely makes use of scenarios as tools to inform thinking about future possibilities and how to manage them. Thus, scenarios are the obvious tool to describe future climate in ways that are relevant to decision-makers. Here, climate scenarios are defined as a discrete set of physically consistent and self-consistent storylines about the future, under a specified set of assumptions. The impacts and consequences of climate scenarios can be explored in considerable quantitative detail, using metrics that range from meteorological (e.g., rainfall rate) to those that are most decision relevant (e.g., flood level, numbers of people affected, and economic loss).

In summary, the development of CCRA3 has highlighted where significant gaps still exist in the climate science evidence which should be filled before CCRA4. Future options have been proposed which will improve end-to-end risk assessments and the uptake of the latest climate science, as well as enable stress-testing of future adaptation options to extreme or worst-case scenarios.

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## Annex 1. Advances in climate modelling since CCRA2

### A1.1 Improvements to climate models

Since CCRA2, significant advances have been made in both global and regional modelling for weather and climate prediction. For climate science serving the UK, a new climate model, HadGEM3, is a key part of a comprehensive new set of UK climate projections (UKCP18) and other applications including global forecasts on timescales of months to a century. HadGEM3 features significant increases in horizontal and vertical resolution in the atmosphere and ocean, as well as improvements in model physics, giving notable reductions in a number of key systematic biases (Williams *et al.*, 2018). The atmosphere model resolution increased from 150km in the horizontal, as used for CMIP5 and IPCC AR5, to 60km, and from 38 to 85 levels in the vertical. The ocean resolution increased from 1° to 0.25° and from 40 to 75 levels.

These enhancements in resolution have delivered significant improvements in the structure of synoptic weather systems and ocean circulation, and in subseasonal and seasonal predictability for the UK, including precipitation (e.g., Scaife *et al.*, 2014). This is associated in part with much improved interactions between the stratosphere and troposphere with higher vertical resolution and better representation of the Gulf Stream with higher ocean resolution.

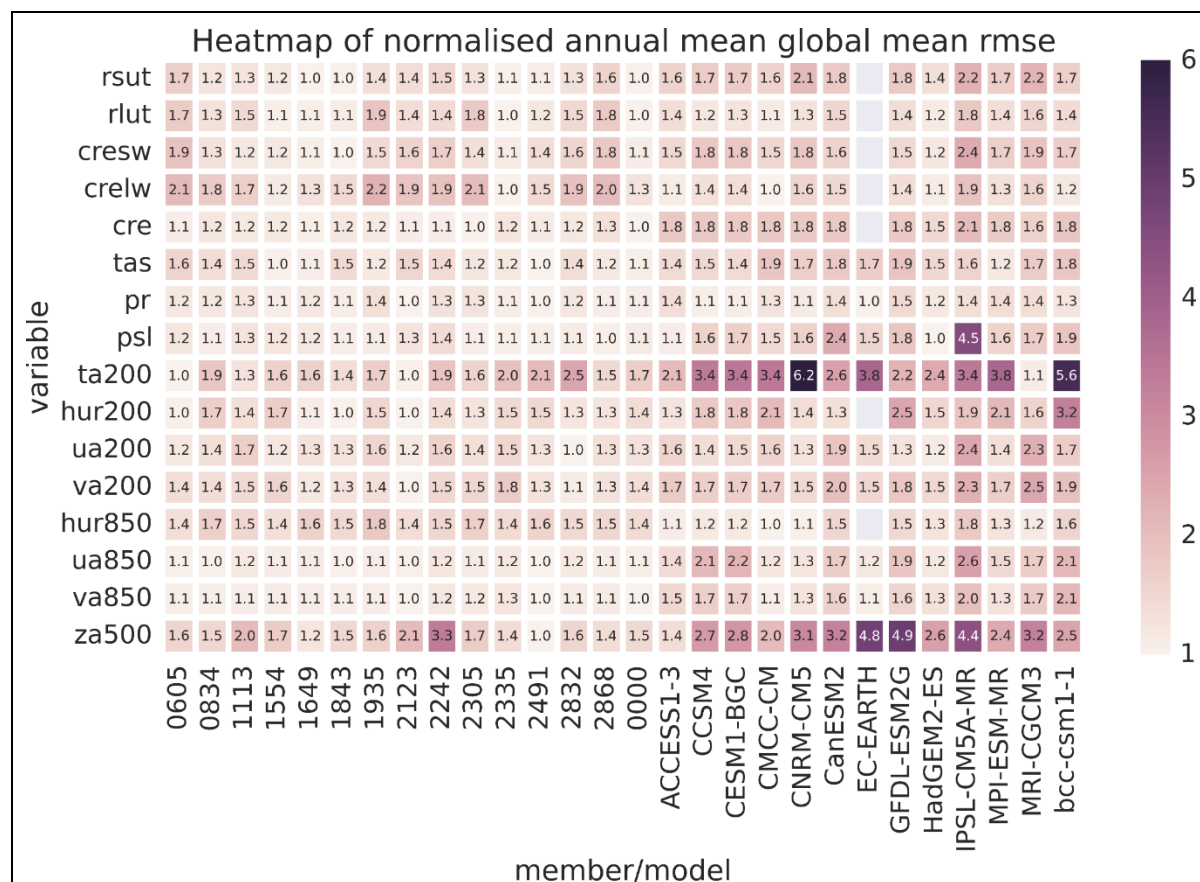
Analysis of the HadGEM3 perturbed parameter ensemble used in UKCP18 showed that, for all members, HadGEM3 out-performs the CMIP5 models across a wide range of climate variables (Figure A1.1 from UKCP18 Land projections: Science Report).

Another advance since CCRA2 has been the creation of a new ensemble of regional climate simulations based on the variants of HadGEM3 used in the perturbed parameter ensemble and driven by boundary conditions from the equivalent global model. So, the regional simulations have also benefited from the improvements in the North Atlantic weather and climate variability in HadGEM3.

The regional model uses a higher resolution of 12km compared with the earlier CORDEX and UKCP09 regional simulations at 25km and gives better representations of the UK landscape and its associated local meteorology, especially in mountainous and coastal areas. Variability in precipitation is higher than in the global model, in better agreement with the observations, and extreme events, such as heavy precipitation and winter cold days, are better represented. Although the ensemble size is still relatively small at only 12 members, the simulations provide meteorologically-consistent scenarios on all timescales from hours to decades and from the local to the national scale, which can be used to drive impacts models. The improved synoptic variability in HadGEM3 and the better representation of extremes in the regional simulations should enable greater stress testing of the UK's resilience across a range of hazards and their impacts.

Finally, UKCP18 included for the first time, internationally, an ensemble of local simulations at an unprecedented resolution of 2.2km, equivalent to the resolution currently being used for operational ensemble weather forecasting for the UK (see UKCP Convection-Permitting Model Projections: Science Report, 2019). Again, the ensemble is based on HadGEM3 and uses the same global model driving fields as the regional 12km ensemble. The aim of this ensemble is to provide information on local extremes, such as sub-daily rainfall and wind gusts associated with, for

example, sting jets. There are numerous examples in operational weather forecasting highlighting the value of this class of simulations, especially for severe weather warnings.



**Figure A1.1** Normalised root-mean-squared errors (RMSE) in global, annual spatial fields of a variety of climate variables from the 28 Strand 2 simulations, averaged over 1981-2000 versus observational estimates from ECMWF reanalysis and satellite data. The climate variables span metrics that cover radiation, temperature, precipitation, winds, surface pressure and geopotential height. The 13 CMIP 5 simulations used in UKCP18 are to the right and the HadGEM3 simulations to the left. The scores are normalised by the RMSE for the best-performing simulation for a given variable, which therefore possesses a value of 1.0. The plot is presented as a “heatmap”, in which simulations with the highest normalised errors, and therefore the worst performance, are shown as the darkest shades of purple. Some entries are missing for EC-EARTH, due to unavailability of data. Reproduced from Murphy et al. (2018)

The UKCP18 2.2km ensemble was published in September 2019 and so has only been used to a limited extent in CCRA3. In future, the value of the convection-permitting model (CPM) ensemble can be expected to be increasingly realised for providing detailed spatial and temporal extreme scenarios to stress test the UK’s preparedness and resilience policies at the local level. This was demonstrated for earlier applications of the CPM for the National Flood Resilience Review analysis of the fit-for-purpose of the Extreme Flood Outlines (National Flood Resilience Review 2016).

In summary, climate science and important aspects of the skill of the climate models have advanced significantly since CCRA2. These advances are embodied primarily in the new family of global and regional models, based on HadGEM3, which is an important part of UKCP18. However, the climate

sensitivity of HadGEM3 (Andrews *et al.*, 2019) is significantly higher than earlier Hadley Centre global models, such as HadCM3 used in UKCP09 and HadGEM1 used in IPCC AR5. It is also higher than the cohort of CMIP5 models, which was used in CCRA2, but in line with a number of recently developed models being used in CMIP6 for the IPCC AR6. As Andrews *et al.* (2019) note, none of the model's forcing and feedback processes are found to be atypical of other models, although the cloud feedback is at the high end.

CCRA3 is framed in terms of trajectories of global warming rather than emissions scenarios. Research commissioned on some of the risks therefore used selected components of the UKCP18 projections representing global warming of approximately 2°C and 4°C by the end of the century. The assessment of other risks draws on literature using other models, projections and scenarios that give approximately 2°C and 4°C global warming by 2100.

## A1.2 Methods for climate projections

This section summarises the methods used for the latest projections of future changes in the UK's climate during the 21<sup>st</sup> Century. It draws on the detailed reports produced for the new UK climate projections UKCP18 (Gohar *et al.*, 2018; Kendon *et al.*, 2019; Murphy *et al.*, 2018; Palmer *et al.*, 2018) the emerging literature from the latest global climate models in preparation for IPCC AR6, and analysis by Hanlon *et al.* (2021a). Comparisons with earlier climate projections are also made, since much of the impacts and risks literature assessed in CCRA3 uses these.

UKCP18 consists of several components which are useful for different aspects of climate change risk assessment.

1. Probabilistic projections of climate over UK land which draw together information from perturbed-parameter ensembles with the HadCM3 model and the multi-model ensemble in CMIP5. These give an estimate of the likelihood of particular changes, e.g., long-term average temperature or precipitation change across the UK, from the present day to 2100. The changes at each gridpoint are independent from each other – they are not intended to provide a coherent picture of change across the country, just likelihood of change in individual locations.
2. A set of global projections at 60km resolution out to 2100 which are spatially coherent, i.e., each individual projection represents climates that could occur simultaneously across the world. Overall, the projected changes across the whole set cover a similar range to those in the probabilistic projections described above, but individual projections are not assigned likelihoods. Within this set, the HadGEM3 model provides a subset of projections. Due to the behaviour of HadGEM3, this subset of projections tends to be at the warmer end of the range of probabilistic projections. The other subset uses projections from other climate models developed by other modelling centres, as part of the 5<sup>th</sup> Coupled Model Intercomparison Project (CMIP5). The range of outcomes from the CMIP5 subset covers a similar range to the probabilistic projections.
3. A set of regional projections of climate over land out to 2100 at 12km resolution, covering the UK. These are driven at their boundaries by output from the global simulations with the HadGEM3 subset of the global projections and provide a more detailed simulation of the



climate at the UK scale. Again, because they use HadGEM3 boundary conditions, the projections are at the warmer end of the range of the probabilistic projections.

4. A further set of local projections of climate over land at 2.2km resolution, for selected time periods during the 21<sup>st</sup> Century. These higher-resolution models are designed to provide a more realistic simulation of key meteorological processes, particularly convection, and are particularly for simulating extreme events such as heavy rainfall or high daily maximum temperatures.
5. A set of projections of long-term sea level rise, storm surges and changes in wave height for UK coastlines
6. A set of projections derived from the above, representing long-term climate states at 2°C and 4°C global warming and a low-emissions scenario

The regional simulations are driven by HadGEM3 boundary conditions, so the output is influenced not only by HadGEM3's higher climate sensitivity but also its representation of important weather regimes. These are summarised in Section A1.3 where they are placed in context with the probabilistic projections and global model simulations. Due to the computational cost of the high-resolution regional simulations with HadGEM3, regional climate change scenarios were only produced with one emissions scenario to allow for the largest possible ensemble size to be utilized in order to cover a wide range of regional climate outcomes. The highest emissions scenario, RCP8.5, was chosen so that the widest range of future levels of global warming could be explored, including the most extreme climate changes considered as low-probability, high-impact scenarios.

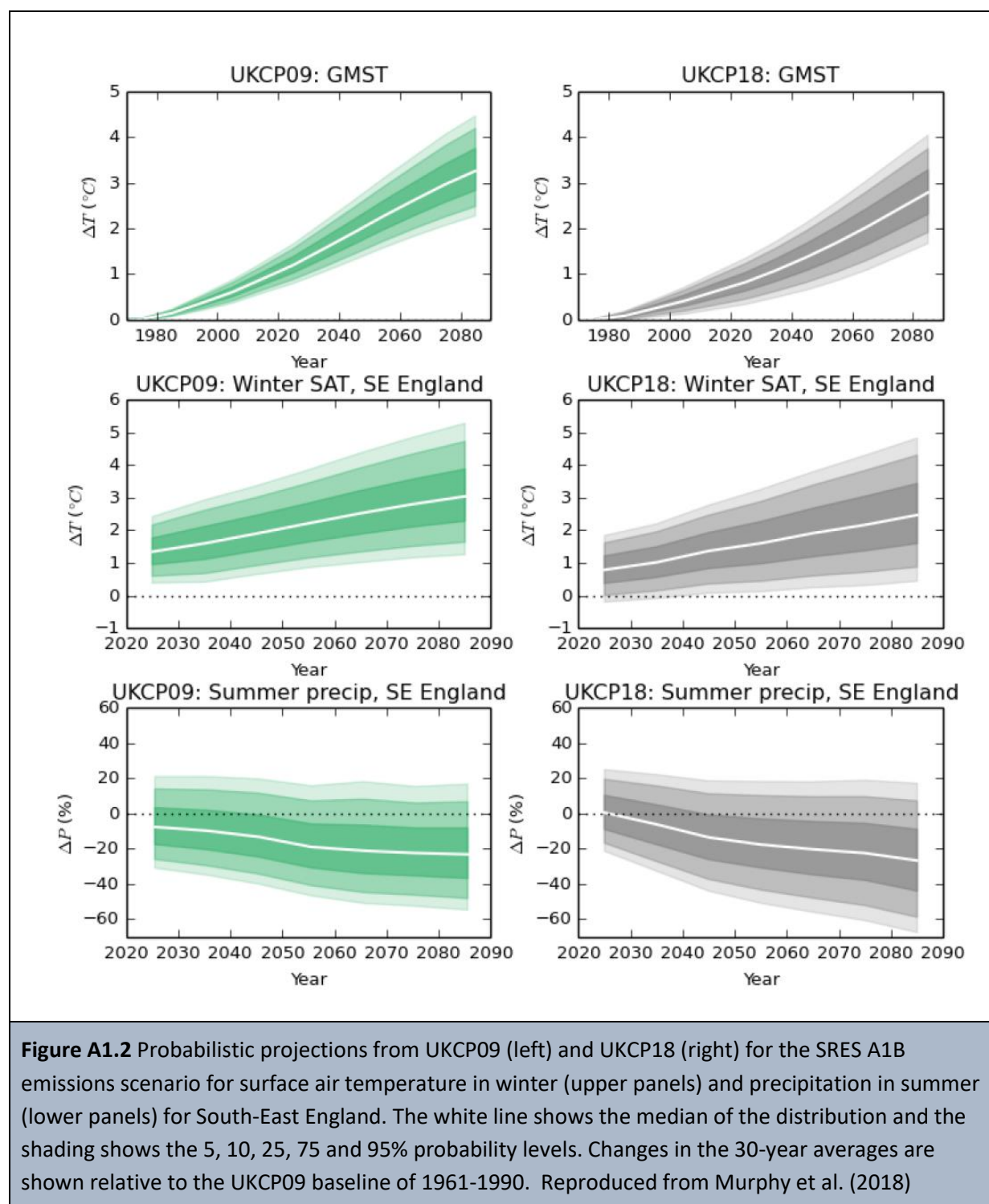
Nevertheless, for many climate impact drivers, the projected regional changes at particular levels of global warming can be considered to be representative of the same level of global warming reached at a later date with a lower emissions scenario and/or as a result of a lower climate sensitivity.

The regional projections basically reflect the driving boundary conditions of HadGEM3. In winter the results mostly lie within the range of the probabilistic projections but indicate slightly wetter and warmer winters than in previous assessments, consistent with the increase in cyclonic weather types in HadGEM3 and its higher climate sensitivity. In summer, however, the regional projections are substantially different and are towards the hotter, drier end of the range of the probabilistic projections. Both Scotland and England are projected to be 1-2°C warmer than the earlier CMIP5 models, associated in part with HadGEM3's higher climate sensitivity. For England, there is a very strong signal for much reduced rainfall, which is in line with the link between the phase of the SNAO and summer rainfall noted earlier and therefore not due entirely to the higher climate sensitivity.

### A1.3 Comparison of UKCP18 with UKCP09 and other climate projections

Figure A1.2 shows that the trajectories of the 30-year average UK climate are very similar in UKCP18 and UKCP09 when considering a consistent emissions scenario, with the differences at any particular percentile level being much smaller than the 5<sup>th</sup> to 95<sup>th</sup> percentile spread. This provides reassurance that the evidence for the ongoing trend towards increased likelihood warmer, wetter winters and hotter, drier summers is unchanged. This consistency with UKCP09 on the overall trajectory of long-term average climate change is important because much of the climate risk literature available for CCRA3 uses UKCP09.

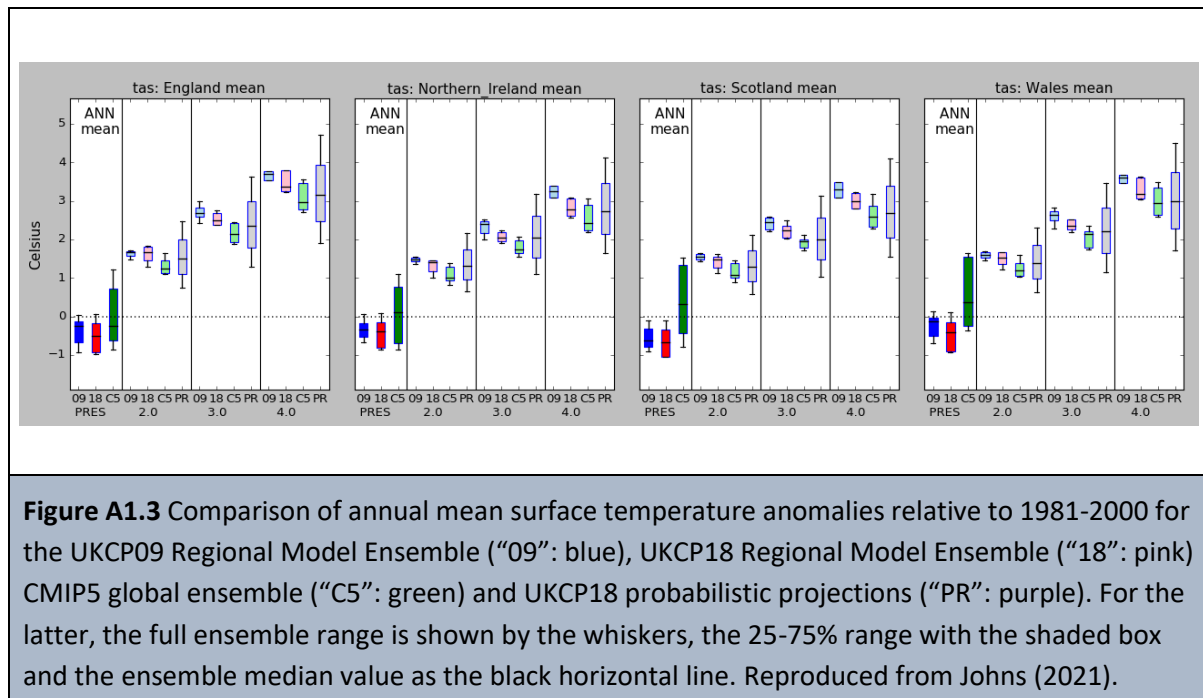




CCRA3 commissioned a detailed comparison of these climate metrics based on processed daily data from the regional climate model (RCM) perturbed parameter ensemble components of UKCP18 and UKCP09 (Johns, 2021). In order to place the UKCP results in a broader modelling uncertainty context, results have also been compared to an ensemble of 13 selected CMIP5 global projections, analysed in a similar way using available daily data. The analysis considered future changes in the metrics of interest through the 21<sup>st</sup> Century relative to a present-day baseline of 1981-2000, with a focus on

changes at specified global warming levels ranging through 1.5, 2, 3 and 4 °C relative to preindustrial.

Reframing the results in terms of 20-year time slices centred on 2, 3 and 4 °C of global mean warming shows that the UKCP18 regional model ensemble actually exhibits relatively lower warming than the UKCP09 regional model ensemble over all UK nations for any given level of global warming (Figure A1.3). However, the UKCP18 results are higher than those based on global CMIP5 model results. Figure A1.3 also shows the bias in the various ensembles for the present day so that the projected climate change can be put in context.



#### A1.4 Emissions scenarios and concentration pathways in the RCPs

Studies of future climate change impacts and risks using climate model projections use different approaches to the representation of future emissions scenarios. Some, such as UKCP09 and UKCP18, use Earth System Models to calculate a more complete climate system response to a given emissions scenario, including modelling the carbon cycle interactively with the atmosphere and oceans. Others, such as CMIP5, do not model the carbon cycle and instead assign a specific scenario of CO<sub>2</sub> concentrations based on other models. In order to compare or integrate results from these projections correctly, it is important to appreciate the differences between these approaches. Unfortunately, for the RCP scenarios, the same terminology is used in the literature for both emissions scenarios and concentration pathways, and this can often lead to a lack of clarity and poor understanding of the context of research studies of climate change risks.

The RCPs (Representative *Concentration* Pathways) are defined in terms of levels of radiative forcing at the end of the 21<sup>st</sup> Century, which is due to particular level of atmospheric concentrations of greenhouse gases and aerosols. Each RCP has a standard pathway of atmospheric CO<sub>2</sub> concentrations, and it is these concentration pathways that are used as input most climate projections of the CMIP5 generation, including those used in the IPCC 5<sup>th</sup> Assessment Report (IPCC,

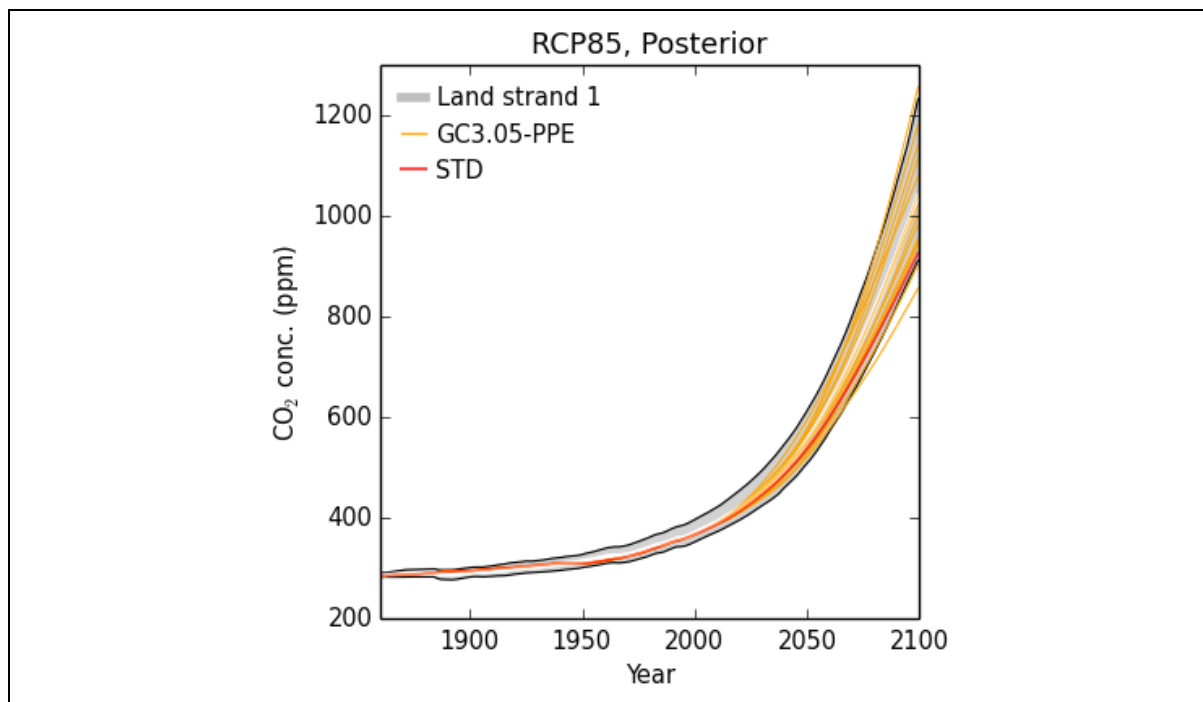
2013). For example, in RCP8.5, the radiative forcing in 2100 is  $8.5 \text{ Wm}^{-2}$ , and the  $\text{CO}_2$  concentration at that time in the standard RCP8.5 concentration pathway is 936 parts per million (ppm) (Booth et al., 2017).

However, the same term (RCP) is also applied to specific *emissions* scenarios that are conventionally associated with these concentration pathways. For example, in the standard RCP8.5 emissions scenario, the cumulative  $\text{CO}_2$  emissions from 2020 to 2100 are 6629 Gigatonnes of  $\text{CO}_2$  ( $\text{GtCO}_2$ )<sup>13</sup>. These emissions scenarios are used in other climate models using a different approach to the main CMIP5 models, taking the emissions as input and then calculating the  $\text{CO}_2$  concentrations within the model. The UKCP18 projections uses this approach.

A critical point about the differences between these approaches is that there is uncertainty in the strength of carbon cycle feedbacks in the climate system, with the result that:

- a) Any given emissions scenario can give rise to a wide range of future concentration pathways
- b) Any specific future concentration pathway can arise from a wide range of emissions scenarios

In UKCP18, the probabilistic projections include an exploration of uncertainties in carbon cycle feedbacks, and hence effectively represent a range of  $\text{CO}_2$  concentrations compatible with each RCP emissions scenario, not just the standard RCP concentration pathways used in CMIP5. This should be borne in mind when comparing the CMIP5 projections with UKCP18 projections using apparently the same scenario - even though both are labelled “RCP”, the scenarios have been applied differently. The standard RCP8.5 concentration pathway used in the CMIP5 projections is in the lower part of the range of concentrations compatible with the RCP8.5 emissions scenario using a coupled climate-carbon cycle model. (Booth et al., 2017; Murphy et al., 2018; Figure A1.4)

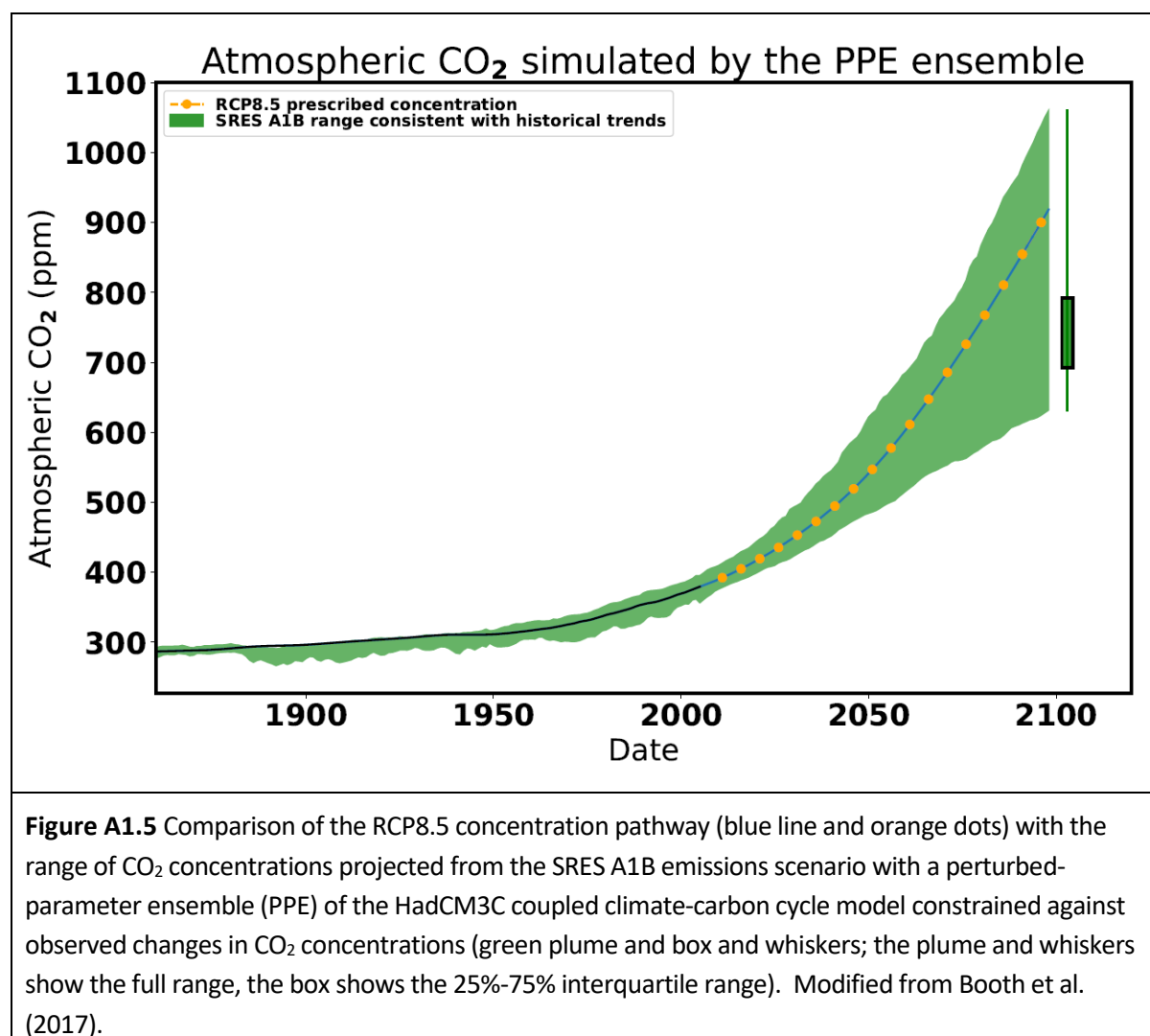


<sup>13</sup> <https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=compare>

**Figure A1.4** Projected changes in atmospheric CO<sub>2</sub> concentration associated with the RCP8.5 emissions scenario. Red (“STD”): the standard CO<sub>2</sub> concentration pathway for RCP8.5 as used in CMIP5. Orange (“GC3.05-PPE”): several CO<sub>2</sub> pathways simulated with Earth System Models driven by the RCP8.5 emissions scenario, including feedbacks between climate change and the carbon cycle, constrained against observations of the historical CO<sub>2</sub> rise following Booth *et al.* (2017). Grey plume (“Land strand 1”): probability distribution of CO<sub>2</sub> concentrations used in the UKCP18 probabilistic projections driven by the RCP8.5 emissions scenario, with 5<sup>th</sup> and 95<sup>th</sup> percentiles in black. Reproduced from Murphy *et al.* (2018).

This difference in methodology is an important factor in causing the UKCP18 RCP8.5 emissions-driven probabilistic projections to simulate a much wider range of levels of global warming by 2100 than the CMIP5 RCP8.5 concentrations-driven projections, with the upper end of the UKCP18 range being considerably higher than that of the CMIP5 range (see Figure A1.3). It is also one reason for very rapid projected warming in the UKCP18 60km resolution global projections with the HadGEM3 perturbed-parameter ensemble (the other reason being the high equilibrium climate sensitivity / transient climate response).

An important implication of this is that climate projections driven by RCP concentration pathways could arise from different emissions scenarios from the ones conventionally associated with the RCP pathways used. For example, the RCP8.5 concentration of 936 ppm can be reached by a much lower emissions scenario than the standard RCP8.5 emissions scenario. In the SRES A1B emissions scenario (Nakićenović, N. *et al.*, 2000), cumulative emissions are approximately two-thirds of those in the RCP8.5 emissions scenario, but in a perturbed-parameter ensemble of a coupled climate-carbon cycle model constrained against observed changes in CO<sub>2</sub> concentrations, these emissions lead to a wide range of CO<sub>2</sub> concentrations by 2100 which include the 936 ppm of the standard RCP8.5 pathway (Figure A1.5).



In conclusion: due to substantial uncertainties in translating emissions to concentrations, there is no single one-to-one relationship between an emissions scenario and a concentration pathway. This can lead to confusion over the interpretation of the scenario and the level of climate change impact that it represents. Nevertheless, the use of the same term “RCP” for both emissions scenarios and concentration pathway is common, so for clarity it is helpful to specify whether particular projections used RCP emissions scenarios or RCP concentration pathways.

## Annex 2: Threshold Exceedance Metrics

A goal of CCRA3 is to look beyond long-term climatic trends to include volatility of the weather and climate at the regional and local scales. It is the case that some of the more costly, disruptive and dangerous impacts of climate change will be associated with increased frequency and/or intensity of extreme weather and climate events. Furthermore, some of these impacts only come into play, or become very serious, when certain meteorological thresholds are exceeded (Table A2.1).

There is also now the possibility of applying threshold exceedance metrics to the UKCP18 2.2km time-slice scenarios, especially those related to extreme daily and sub-daily rainfall linked to embedded frontal convection and summer thunderstorms, to investigate how the current risk evolves under climate change. Similar to the UNSEEN methodology we can use the 12-member ensemble for 1981-2000 to provide 240 ‘years’ of synthetic observations of the current risk of exceeding certain impact thresholds. This will add to our understanding of the baseline risk from extreme events, which is currently very limited due to the shortness of the observational record. The same analysis can then be applied to the 240 ‘years’ for 2021-2040, which will provide a first assessment of how these metrics may change under near-term climate change. This may provide a valuable tool for CCRA4.

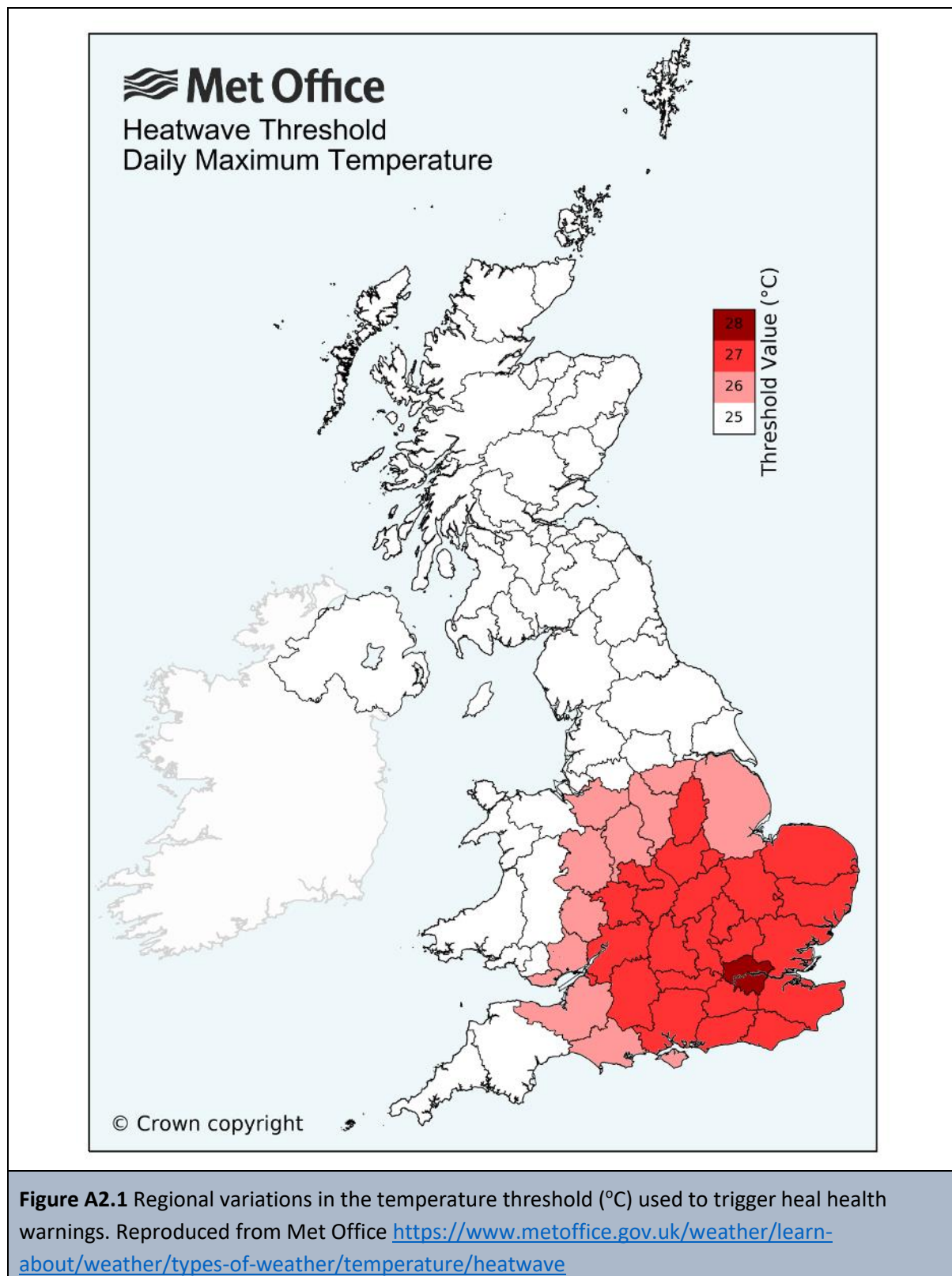
Table A2.1: Impact indices		
Index	Threshold	Impact relevance
<b>Frost Days</b>	Daily minimum temperature below 0°C	Cold-weather disruption due to higher than normal chance of ice and snow.
<b>Icing Days</b>	Daily maximum temperature below 0°C	More extreme than frost days, so more severe cold-weather impacts.
<b>Tropical Nights</b>	Daily minimum temperature above 20°C	Health impact due to high night-time temperatures with potential for heat stress. Vulnerable people at increased risk of hospital admission or death.
<b>Summer Days</b>	Daily maximum temperature above 25°C	High daytime temperatures with health impacts for vulnerable people at risk of hospital admission or death. Transport disruption – e.g., track buckling on railways.
<b>Rainfall meeting National Severe Weather Warning Service (NSWWS) criteria</b>	Thresholds, which vary regionally, and is applied as proxy for Low/Medium/High impacts	Informative for estimating periods of increased risk of river flooding (fluvial flooding only). Note these are not appropriate for assessing pluvial flooding (surface water flooding).
<b>Drought Severity Index</b>	This index is not threshold based. Instead, it is calculated with 3-, 6-, 12- and 36-month rainfall deficits	3-month – meteorological/agricultural drought, a short intense dry period leading to low soil moisture levels impacting crop growth.  6-month – longer and higher impact agricultural drought.

		12-month – hydrological drought leading to low water supply nationwide.  36-month – longer term hydrological drought leading to low water supply nationwide.
<b>Wind gusts meeting National Severe Weather Warning Service (NSWWS) criteria</b>	Thresholds, which vary regionally, and is applied as proxy for Low/Medium/High impacts	Transport disruption, infrastructure or building damage, bridge collapse and trees falling
<b>Growing Degree Days</b>	Daily Mean temperature above 5.5°C	Energy available for plant growth over a year. Not a measure of season length.
<b>Heating Degree Days</b>	Daily Mean temperature below 15.5°C	Indicator of meteorological contribution to energy demand for heating.
<b>Cooling Degree Days</b>	Daily Mean temperature above 22°C	Indicator of meteorological contribution to energy demand for cooling.

Exceedance metrics are currently used in Met Office National Severe Weather Warning Service (NSWWS), which issues warnings when severe weather has the potential to impact the UK. These warnings are based on a combination of the likelihood of the weather event occurring at any location, and the severity of the impacts if that event happens, where the severity is based on historical links between severe weather and its impacts in different parts of the country. This geographic variation in thresholds reflects the variations in both the exposure of populations and infrastructure, as well as the vulnerability of natural and human systems to these extreme conditions.

Alongside the NSWWS, the Met Office also produces a ‘heat health watch’ service for health professionals, contingency planners and emergency responders for planning purposes. This metric is based on exceedance of daily maximum temperature thresholds for least 3 consecutive days. Again, the thresholds vary geographically, as shown in Figure A2.1 and take account of the urban heat island effects in London.





The World Climate Research Programme (WCRP) and World Meteorological Organization (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI) have defined a set of 27 core indices



(the 'ETCCDI' indices<sup>14</sup>) which can be derived from land surface observations of daily temperature and precipitation. A selection has been used in the Met Office's State of the UK Climate reports (Kendon *et al.*, 2018 and McCarthy, 2018) to study observed changes in the UK climate. These can be used in CCRA3 to inform possible changes in the frequency of threshold exceedance, which may have an impact on natural, human and business systems. These differ from the NSWWS metrics which focus on extreme events.

2.2km CPM timeslice scenarios for 1981-2000 and 2021-2040 to provide new estimates of the baseline and near-term climate change risks associated with extreme events at the local scale. For example, based on 3 hourly rainfall, exceedances of 30mm/hour (and potentially 100mm/hour) at any location are currently being studied with respect to surface flooding.

Table A2.2, based on the NSWWS, shows the threshold exceedances that are likely to have a high impact today, and provide a suitable baseline for considering high impact exceedances in the future, where adaptation may be required. The metric refers to any location in the geographical region. Daily rainfall is used to inform forecasters on the possibility of river flooding and these metrics would be applicable to the UKCP18 12km simulations.

<b>Table A2.2 Met Office National Severe Weather Warning Service (NSWWS) thresholds</b>		
<b>NSWWS Index based on 12km UKCP18</b>	<b>Geographical Region</b>	<b>Exceedance Metric</b>
<b>Max 10m Wind gust (winter)</b>	South East England	≥ 70 mph
<b>Max 10m Wind gust (winter)</b>	Highlands and Islands	≥ 90 mph
<b>Max 10m Wind gust (winter)</b>	Rest of the country	≥ 80 mph
<b>Max 10m Wind gust (summer)</b>	South East England	≥ 65 mph
<b>Max 10m Wind gust (summer)</b>	Highlands and Islands	≥ 80 mph
<b>Max 10m Wind gust (summer)</b>	Rest of the country	≥ 70mph
<b>24-hour precipitation</b>	England and Wales	≥ 80 mm
<b>24-hour precipitation</b>	Northern Ireland	≥ 80 mm
<b>24-hour precipitation</b>	NW Scotland	≥ 80 mm
<b>24-hour precipitation</b>	SW Scotland	≥ 65 mm
<b>24-hour precipitation</b>	South and East Scotland	≥ 55 mm
<b>24-hour precipitation</b>	NE Scotland	≥ 75 mm
<b>Maximum Temperature</b>	Geographically varying (see Figure)	≥ 25-28°C for 3 consecutive days

<sup>14</sup> [http://etccdi.pacificclimate.org/list\\_27\\_indices.shtml](http://etccdi.pacificclimate.org/list_27_indices.shtml)

The ETCCDI indices (Table A2.3) identify aspects of our changing climate that influence the functioning of natural ecosystems and aspects of demands on infrastructure. They complement the NSWWS extreme indices.

<b>Table A2.3</b> World Meteorological Organization Expert Team on Climate Change Detection and Indices (ETCCDI) Indices			
<b>ETCCDI Index based on 12km UKCP18</b>	Variable	Threshold	Count
<b>Frost Days</b>	Daily Minimum Temperature	< 0 °C	Days below this threshold
<b>Icing Days</b>	Daily Maximum Temperature	< 0 °C	Days below this threshold
<b>Tropical Nights</b>	Daily Minimum Temperature	> 20 °C	Days above this threshold
<b>Summer Days</b>	Daily Maximum Temperature	> 25 °C	Days above this threshold
<b>Growing Degree Days</b>	Daily Mean Temperature	> 5.5 °C	Degrees above this threshold per day
<b>Heating Degree Days</b>	Daily Mean Temperature	< 15.5 °C	Degrees below this threshold per day
<b>Cooling Degree Days</b>	Daily Mean Temperature	> 22 °C	Degrees above this threshold per day

UK Climate Risk  
Independent  
Assessment (CCRA3)

# **Technical Report**

## **Chapter 2:**

## **Method**

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## Executive Summary

This chapter sets out the methodology for the Third UK CCRA Technical Report (CCRA3). The Technical Report informs the CCRA3 Advice Report, which is written by the Climate Change Committee, and these two documents together are the core components of the CCRA3 Independent Assessment.

In line with the Climate Change Act 2008, the objective of the CCRA is to consider current and future climate-related risks and opportunities to the UK, and the extent to which current or planned policies address these. To help guide this, the CCRA3 Technical Report uses the following key question:

**Based on the latest understanding of current and future climate risks and opportunities, as well as current and planned adaptation, what should the priorities be for the next National Adaptation Programme and adaptation programmes of the devolved administrations?**

The aim of the CCRA3 Technical Report is to inform planned adaptation from government, agencies, regulators, etc., including both direct intervention and/or to create the enabling environment to help others adapt (e.g. the private sector, households). It seeks to inform the adaptation programmes of the individual countries of the UK (England, Northern Ireland, Scotland and Wales) and this determines the aggregation and reporting level. The priority for the Technical Report is, therefore, to identify where action is needed in the next five years to manage climate change risks or opportunities that may arise over the short, medium and longer-term.

As with CCRA2, the CCRA3 Technical Report uses a synthesis approach. It draws on a large body of peer-reviewed scientific literature and other quality-assured literature on climate change, risks and adaptation, complemented by new research studies in key areas. This requires a harmonised and consistent approach to consider and collate evidence from different sectors and source material: this chapter sets out this approach.

The method developed in CCRA3 builds on requirements set out by Defra and the devolved administrations and an initial method statement developed by the Climate Change Committee (CCC). This was developed further by the CCRA3 Evidence method team authors. It uses the same broad approach as CCRA2, but with some evolution to reflect lessons from CCRA2 and the second round of national adaptation programmes, as well as developments in the climate risk assessment and adaptation literature over the past five years.

The CCRA3 Evidence method is based on the prioritisation of risks and opportunities using an analysis of urgency. This seeks to identify where action is most urgently needed over the next five-year period using three questions:

1. What is the current and future level of risk/opportunity?
2. Is the risk/opportunity being managed, based on government commitments and other adaptation actions?
3. Are there benefits to further action in the next five years, over and above that already planned?

For the CCRA3 Technical Report, we have aligned the methodology to the three questions above, thus there are three steps:

- Step 1) Analysis of the magnitude of current and future risks and opportunities;
- Step 2) Analysis of the benefits of current and planned adaptation;
- Step 3) Analysis of overall urgency and the benefits of additional adaptation.

For the third of these steps, the CCRA3 uses a complementary framework to help to identify adaptation priorities, as well as what type of additional action could be useful. This approach builds on a well-established literature that was also included in CCRA2. It aims to identify three types of early adaptation priorities that can help address risks and opportunities within the next five-years:

- To address any current adaptation gap by implementing ‘no-regret’ or ‘low-regret’ actions that reduce risks associated with current climate variability, as well as building future climate resilience.
- To intervene early to ensure that adaptation is considered in near-term decisions that have long lifetimes and therefore reduce the risk of ‘lock-in’, such as for major infrastructure or land-use developments.
- To fast-track early adaptive management activities, especially for decisions that have long lead times or involve major future change. This can enhance learning and allows the use of evidence in forthcoming future decisions.

These three priorities are not mutually exclusive, and a combination of all three is often needed as part of a portfolio at the national level.

At the end of this analysis, based on the evidence, each risk or opportunity is ranked into one of four urgency scores: i) “more action needed”; ii) “further investigation”; iii) “sustain current action”; or iv) “watching brief”.

A number of updated or new elements have been included in the CCRA3 Evidence method. These include the following:

- A new set of UK Climate Projections were published in 2018, 2019 and 2020, called UKCP18. However, it takes several years for the risk and impact literature to use these projections in published studies, and much of CCRA3 is therefore based on literature that uses the previous set of projections, UKCP09. CCRA3 has therefore assessed what has changed from UKCP09 to UKCP18, and has produced guidance on how to interpret exiting literature using the new UKCP18 results (see also Chapter 1 (Slingo, 2021) and section 2.2 of this chapter).
- There is a greater focus in CCRA3 on looking at changes in climate variability (volatility) and new methods for considering unprecedented events that could occur in the current climate. CCRA3 has also considered the potential risks of low-likelihood, high-impact outcomes, which includes High++ scenarios and major discontinuities (globally or regionally) (see Chapter 1 (Slingo, 2021) and section 2.2 of this chapter).
- CCRA3 has considered interacting risks and interdependencies for each risk / opportunity, rather than as part of a cross-cutting chapter (as in CCRA2). There is also consideration of the inequalities associated with risks and opportunities.



- There is a greater focus on considering the type of further adaptation that could be possible, and on the benefits of additional action. A lesson from CCRA2 is that evidence to inform adaptation needs to be collected and assessed earlier in the analysis. CCRA3 therefore has a greater emphasis on the risks of lock-in and thresholds, as part of step 1 (see section 2.3). There is also more emphasis on adaptive management, encouraging the consideration of evolving risks over time, including a more explicit linkage to CCRA4 (see section 2.3).
- There has been more consideration of the economic costs (or benefits) of individual risks and opportunities (reported in a separate monetary valuation analysis) and an analysis of the indicative costs and benefits of further adaptation. n the indicative costs and benefits of further adaptation.
- Finally, during the period that the analysis for the CCRA3 Technical Report was undertaken, the UK, Scottish and Welsh Governments adopted Net Zero greenhouse gas emissions targets into law. The measures needed to achieve Net Zero may be sensitive to climate hazards, particularly in the buildings and land use sectors. To investigate this, CCRA3 has considered possible relevant climate risks or opportunities for different types of mitigation measures, and also considered synergies and trade-offs between mitigation and adaptation actions (see section 2.5).

## 2.1. Introduction

### 2.1.1 Context and Objectives

**The UK's Climate Change Risk Assessment (CCRA) aims to analyse the risks and opportunities from climate change to the UK, with the goal of informing the priorities for the UK Government's National Adaptation Programme (NAP) as well as the adaptation programmes of the devolved administrations (DAs).**

The UK CCRA is undertaken on a five-year rolling cycle and is now on its third cycle. This chapter sets out the approach used for the **Third CCRA Technical Report**, to be published in 2021. The objective of the Technical Report is to review and analyse the evidence on priority risks and opportunities for England, Northern Ireland, Scotland and Wales and by doing so, to help provide information of relevance for the next round of Government-led adaptation programmes. The Technical Report informs the CCRA3 Advice Report, which is written by the Climate Change Committee, and these two documents are core components of the CCRA3 Independent Assessment. This Assessment informs the CCRA3 Government Report (due for publication in 2022) and the third NAP and the third adaptation programmes of the devolved administrations (DAs), due to be published from 2023. The information in the CCRA3 Technical Report is, however, also likely to be of interest to a wider audience.

For practical purposes, the CCRA3 Technical Report sets out to address the following key 'exam' question:

**Based on the latest understanding of current and future climate risks and opportunities, as well as current and planned adaptation, what should the priorities be for the next National Adaptation Programme and adaptation programmes of the devolved administrations?**

These adaptation programmes may include direct public sector action (by government, agencies, regulators, etc.), but also interventions that create the enabling environment for others to adapt, i.e. for utilities, the private sector and households. To provide this information, the CCRA focuses on the urgency of risks and opportunities. Urgency is defined as a measure of the level of action that is needed in the next five years to reduce a risk or realise an opportunity from climate change, noting that these near-term actions may address risks or opportunities in the short, medium or long-term. To ensure that the information provided is relevant for the respective adaptation programmes, the assessment is undertaken for each individual country (England, Northern Ireland, Scotland and Wales), rather than for the UK.

In addition, unless it conflicts with the primary aim, the CCRA3 Technical Report also has a set of secondary goals, which are:

- To inform investment and policy decisions where there are material climate risks for other organisations or actors, e.g. for the private sector (including small to medium sized businesses) or households. This has links to recent initiatives on financial climate risk disclosure and reporting (TCFD, 2017; NGFS, 2019) and also the UK Green Finance Strategy (HMG, 2019);

- To show progress from CCRA1 (HRW, 2012a) and from CCRA2 (CCC, 2016) on how our understanding of the level of current and future risk, as well as the management of these risks by Government, has changed; and
- To act as a stepping-stone to CCRA4 in terms of the approach, framing and information needs.

The CCRA3 Technical Report draws on a well-informed practitioner community and a rich legacy of previous climate risk assessments. It updates the previous CCRA2 by drawing on evidence produced in the intervening five years. It also includes an update to the methodology used for the assessment, taking advantage of the fact that the five-year UK CCRA cycle allows for a process of evaluation and learning. This has led to an evolution in the method used for successive assessments, i.e. from CCRA1 to CCRA2, and CCRA2 to CCRA3.

In the first and second CCRAs, the assessment of risks was presented in an Evidence Report. In CCRA3, the Independent Assessment consists of a substantial set of reports and other documents including this Technical Report and the CCC's Advice Report. As with the CCRA2 Evidence Report, the CCRA3 Technical Report is based on a synthesis exercise, rather than a new national quantified assessment. It draws on the large body of peer-reviewed scientific literature and grey literature on climate change, risks and adaptation in the UK, complemented with new CCC commissioned research in key areas. It uses this evidence alongside expert judgement in assessing risks and opportunities, building on expertise in the international context (e.g. Mach et al., 2017) as well as previous CCRAs. However, this synthesis approach means that the CCRA3 draws on literature that has used different methods, scenarios and assumptions.

**The key aim of the CCRA3 method chapter is to set out a harmonised approach to: gather evidence from the wide range of source material; to analyse this evidence consistently; and to present it in ways that make it easier for the UK Government and the devolved administrations to respond. This chapter sets out this approach.**

The method developed for the CCRA3 Technical Report responded to requirements set out (in a document) by Defra and the devolved administrations (produced in 2018).

It was further developed by the CCRA3 Evidence method team authors, working in partnership with the Climate Change Committee, who led the overall programme to produce the Independent Assessment, and with inputs and comments from the peer review process. The method development drew on lessons from the second CCRA Evidence Report (CCRA2), published in 2016 (CCC, 2016), the latest climate science including the new UK Climate Projections (UKCP18), and the updated approaches to climate change risk and adaptation assessment presented in the IPCC Fifth Assessment Report (IPCC, 2014a), the Special Reports on Global Warming of 1.5°C (IPCC, 2018a) and on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019). A summary of the methodological development of the three CCRAs over time is presented in Table 2.1 below, followed by discussion of a number of key updates of relevance in CCRA3.

**Table 2.1** Evolution of the CCRA method over time.

	<b>CCRA1</b>	<b>CCRA2</b>	<b>CCRA3</b>
<b>Objective and aims</b>	Quantification of risks / opportunities (impacts)	Assessment of risks / opportunities to inform adaptation	Assessment of risks / opportunities to inform adaptation and initial steps towards adaptive management
<b>Approach</b>	New analysis of all risks using standardised approach	Synthesis, supported by targeted new research	Synthesis, supported by targeted new research and inclusion of new climate projections
<b>Direct funding available*</b>	Approximately £3.5 million	Approximately £0.7 million	Approximately £1.8 million
<b>Method to assess risk / opportunities</b>	Quantitative or semi-quantitative impact assessment	3 step urgency framework	3 step urgency framework, with additional method development
<b>Identification of risks / opportunities</b>	Very wide initial review, with focus down on 100 or so most important	Initial list provided by Government and DAs, reviewed and extended based on evidence to ~55 risks and opportunities	Initial list provided by Government and DAs, reviewed and extended based on evidence to ~65 risks and opportunities
<b>UK climate Projections</b>	UKCIP02 and UKCP09	UKCP09	UKCP09, UKCP18, EuroCORDEX
<b>Global climate projections</b>	N/A	CMIP5	CMIP5, CMIP6, HELIX, UKCP18 global
<b>Economic analysis</b>	Indicative valuation of risks and opportunities	Not included	Indicative valuation of risks and opportunities, plus initial consideration of costs and benefits of further adaptation

\* It is highlighted that all three CCRA, but especially the synthesis assessments undertaken in CCRA2 and CCRA3, benefited from considerable levels of in-kind support. This included the time contribution of the CCC secretariat, as well as the inputs from contributor authors which were unpaid. The total costs of undertaking CCRA2 and CCRA3 is therefore much higher than shown in the table.

**Climate Science.** Since CCRA2, there has been the publication of new climate projections for the UK (Lowe et al., 2018; Murphy et al., 2018; Palmer et al., 2018). The CCRA3 Technical Report makes use of UKCP18 as far as possible, and bespoke analysis was carried out to help teams re-assess existing published evidence on future impacts (which is often based on UKCP09) in light of the new projections (see Chapter 1: Slingo, 2021). However, the Technical Report also draws on scenarios and studies that are not based on UKCP18 in order to ensure evidence is drawn from the widest possible base of research.

**Identification of risks and opportunities.** There are a very large number of potential risks and opportunities from climate change in the UK, indeed, the CCRA1 Evidence Report (HRW, 2012a) identified almost 1,000 of these following a series of stakeholder workshops to come up with a ‘long list’. This was then reduced down to the most important 100 or so based on a set of evaluation criteria. The approach adopted in CCRA3 is the same as the second CCRA (CCC, 2016) and focuses on the most important risks and opportunities as identified by the UK Government and devolved administrations, with some additions from the Technical Report authors and inputs from stakeholder workshops. This approach is therefore selective (rather than comprehensive). Although driven by the end user, this approach to risk selection runs a risk that some risks or opportunities (including unknowns) are poorly addressed, though CCRA3 has paid greater attention to the consideration of low-likelihood, high impact scenarios and events than previous CCRA3s (see later section).

**Consideration of Adaptation.** The role of the CCRA3 Technical Report – as part of the analysis of urgency - is to assess whether current and planned adaptation is managing risks and opportunities, and what adaptation gaps might be present. For the CCRA, an adaptation gap is considered to exist if risks (or opportunities) are not being managed (see section 2.7). This provides a clearer sense of where action is most urgently needed. Following a specific request from Government, a greater emphasis is given in CCRA3 to identifying where adaptation action is likely to be most ‘urgent’ between 2022 and 2027. This includes an indicative analysis of what form this additional adaptation could take, and possible costs and benefits, while noting it is not the role of the CCRA3 Technical Report to identify adaptation policies or make recommendations.

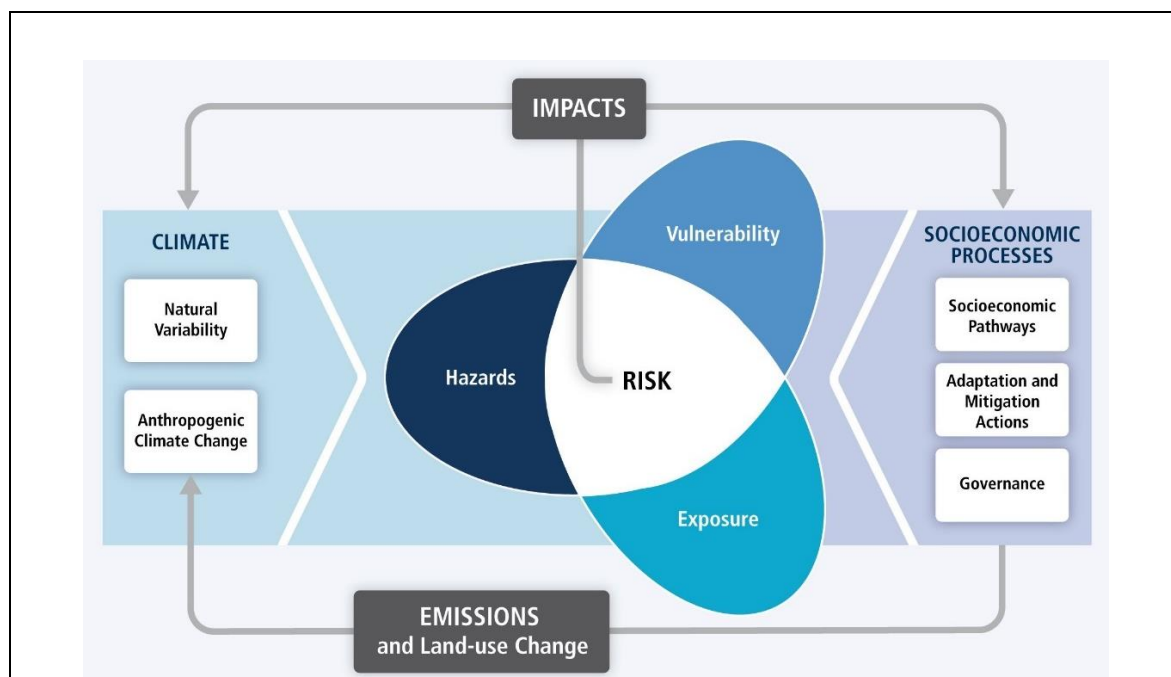
**Net Zero.** During the time period that the CCRA3 was being undertaken, the UK Government adopted a Net Zero greenhouse gas emissions target, as an amendment in the Climate Change Act. The Scottish Government committed to a target of Net Zero emissions of all greenhouse gases by 2045 and the Welsh Government has announced a 95% reduction in greenhouse gas emissions by 2050 with an ambition to reach Net Zero. This has important implications for future socio-economic scenarios and mitigation-adaptation linkages. To respond to this, an additional analysis was included in the second round of the CCRA3 evidence analysis. This undertook an initial analysis on the possible influence of climate risks on Net Zero measures, and considered mitigation-adaptation linkages.

### 2.1.2 Key Terms

In the context of the CCRA3 Technical Report, ‘risks’ are defined in line with the climate change literature (IPCC, 2014a), i.e. the potential for adverse consequences of climate-related hazards, based on their likelihood of occurrence, and taking account of exposure and vulnerability. In CCRA3, the term ‘risk’ is used to identify negative consequences from climate change, and the term ‘opportunity’ to identify positive consequences. A full glossary has been developed for CCRA3 and a number of the key terms are presented in Box 2.1. This draws primarily on the IPCC 5<sup>th</sup> Assessment Report (AR5) Core Concepts (IPCC, 2014a), the IPCC Glossary (IPCC, 2014b) and the IPCC Special Report on Global Warming of 1.5 °C (SR1.5) (IPCC, 2018b), but with additions on the new elements introduced in CCRA3. It has been reviewed and agreed by the CCRA3 technical team, peer reviewers and Government stakeholders.

**Box 2.1** Key concepts and terms used in CCRA3.

The main definitions in CCRA3 draw on the IPCC 5<sup>th</sup> Assessment Report (IPCC, 2014b) and the IPCC core concepts (IPCC, 2014a) and key terms are summarised below.



**Box 2.1 Figure 1.** Core Concepts of the IPCC 5<sup>th</sup> Assessment Report WG II. Reproduced from IPCC, 2014a.

**Risk** - The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate-related hazard on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence. Source IPCC SR1.5. Note that in CCRA3, the term risk is used for negative consequences (i.e. threats).

**Opportunity** - The potential for a beneficial consequence, as a result of a changing climate (the propensity to be beneficially affected). Source: CCRA3 Method Chapter Authors.

**Exposure** - The presence (of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets) in places and settings that could be adversely affected. IPCC, AR5.

**Vulnerability** - The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. Source IPCC, AR5.

**Hazard** - The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. In the IPCC, hazard refers to climate-related physical events or trends. Source IPCC AR5.

**Impacts** - Effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health status, ecosystems, economic, social, and cultural assets, services (including environmental), and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. Source IPCC AR5.

**Adaptation** - The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects. Source IPCC, AR5. This includes: Incremental adaptation - Adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale. Transformational adaptation - Adaptation that changes the fundamental attributes of a system in response to climate and its effects. Source IPCC AR5.

**Autonomous adaptation** - IPCC AR5 defined this as adaptation in response to experienced climate and its effects, without planning explicitly or consciously focused on addressing climate change (spontaneous adaptation). However, CCRA3 does not use the term autonomous adaptation. Instead, it considers two elements: reactive adaptation, i.e. a response to the changing climate experienced rather than a pro-active planned approach, as well as non-governmental planned adaptation (i.e. anticipatory adaptation undertaken by other organisations, e.g. private sector).

**Resilience** - IPCC AR5 defines as: the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation. However, the term resilience is now used very widely, in different ways, and as a consequence in CCRA3 we try and avoid the term due to the lack of a commonly applied definition. The exception is where it is used in existing Government policies, or in plans or actions as stated by the private sector or other groups, noting in such cases the specific definition should be included.

**Adaptation pathway** - A generic term that involves the analysis of adaptation options over time to changing risk levels. This term has been applied in a number of different ways, which include: i): Adaptation roadmaps or pathway frameworks, which consider portfolios of adaptation that change over time, to allow analysis of the timing and sequencing of adaptation and identify priorities; ii) Adaptive management, which is an iterative cycle of monitoring, research, evaluation and learning, i.e. a process, that is used to improve future management strategies (also called iterative risk management); iii) Dynamic adaptation route-maps, which focus on decision making under uncertainty and identify adaptation tipping points (or turning points), the point at which a particular action is no longer adequate for meeting the plan's objectives, that act as triggers for a change in adaptation. Source: CCRA3 Method Chapter Authors.

**Socioeconomic scenario** - A scenario that describes a possible future in terms of population, gross domestic product, and other socioeconomic factors relevant to understanding the implications of climate change. Source, IPCC AR5.

**Lock-in** - Early actions or decisions that involve long lifetimes or path dependency, which will potentially increase future risk or vulnerability and that are difficult or costly to reverse later (irreversibility). This can be from a 'business-as-usual' action or decision, from a lack of an action or decision, or from a maladaptive action or decision. Source: CCRA3 Method Chapter Authors.

## 2.2. Developments in the CCRA3 Methodology

The UK Climate Change Act (2008) set out the requirement to complete a Climate Change Risk Assessment (CCRA) every five years, followed by a National Adaptation Programme. This repeat cycle provides the opportunity to review and learn, and thus iteratively improve each CCRA (and subsequent NAP). In line with this, a number of methodological updates have been included in this CCRA Technical Report. These improvements have drawn on the lessons from CCRA2, as well as changing practices on risks and adaptation assessment from the literature. Alongside this, there was the publication of UKCP18 and a new set of CCC commissioned research was published. These developments are set out in this section.

### 2.2.1 Evaluation and Lessons from CCRA2

Following the first CCRA, a number of formal evaluations of the Evidence Report were undertaken (Wilby, 2012; HRW, 2012b; Watkiss and Hunt 2012). These provided recommendations that were used in the methodology update and subsequent implementation of CCRA2 (see Table 2.1). There were also several academic reviews of CCRA1 (Tangney, 2017; Tangney and Howes, 2016).

There was not a formal evaluation of the CCRA2 Evidence Report. However, the CCC produced a lessons report, based on feedback from its Adaptation Committee, as well as Evidence Report authors and the Customer Group of the CCRA. This concluded that distilling the evidence into urgency scores was an effective way to communicate the results in a meaningful way for Government. It also reported that the governance arrangements worked well, i.e. the use of an IPCC-like synthesis approach, with lead contributors and a larger group of contributing authors, overseen by the CCC's Adaptation Committee, acting to coordinate the whole project with independence from Defra. The approach, combined with a two-stage peer and stakeholder review process, delivered an Evidence report that was authoritative and usable. However, the lessons report identified that the success of the project relied heavily on goodwill (given that most authors were not paid), and that the length of the process created challenges. It was also difficult to differentiate risks by scenario (i.e. between the 2°C and 4°C global temperature increase by 2100, relative to pre-industrial), due to the evidence available and the resource constraints. There was also insufficient information on common socio-economic scenarios for the UK. The synthesis approach also made it difficult to assess the magnitude of risks with little evidence or inconsistent assumptions from different evidence sources. There was considered to be insufficient cross-sectoral analysis in the report. Finally, some chapters struggled to get buy-in or material from Government Departments, indicating a need for an improved Government review process. There has also been some academic literature that has compared and evaluated CCRA1 and CCRA2 and made suggestions on future risk assessments (e.g. Howarth et al., 2018), particularly on some aspects of method, operationalisation and better communication.

The CCC consulted with Government (the key users of the Evidence Report), to get feedback on improving the CCRA method. This led to a CCRA3 Requirement Document, produced by Defra and the devolved administrations, and also represented the views of other government departments as fed in using a consultation process. This included the following key requests for CCRA3:



- To inform the adaptation plans of the UK Government and the devolved administrations, and to help this, make the outputs and key messages more accessible (e.g. greater use of infographics, guidance on entry points for outputs, shorter, crisper and less technical summary reports);
- To use a more systems-based approach than CCRA2 to take better account of interdependencies and interactions;
- To take account of new evidence on climate projections (namely UKCP18, most of which was published in November 2018, with a further set of high-resolution projections published in September 2019);
- To consider different future global warming scenarios, including those associated with a 2°C and a 4°C increase in global mean temperature by the end of the century, relative to pre-industrial.
- To use the urgency framework developed for CCRA2, refining it to identify a smaller number of specific priorities for the next five-year period;
- To avoid recommendations about the risk appetite for addressing risks, or on how to adapt, since those are policy or operational decisions. However, where appropriate, and for consistency with CCRA2, to include consideration of some adaptation scenarios that go beyond planned adaptation.
- There was also a subsequent request, as part of discussions with Defra and the DAs, to assess risks and opportunities in monetary terms, and to consider the indicative costs and benefits of adaptation, i.e. to include more economic analysis than in CCRA2.

As part of the CCRA3 methodology development, a rapid evaluation of CCRA2 was also undertaken by the methodology chapter team. This found that the smaller number of risks in CCRA2 (56) allowed a more focused assessment. However, while the use of literature review and synthesis did provide a good evidence base, there was not the same quantitative information of magnitude as generated in CCRA1, and less direct comparability between risks, although this was not considered to be detrimental to the final Evidence Report. The use of the urgency framework was considered a particularly useful addition, as this focused the evidence towards a policy-first approach (Ranger et al., 2010) that informs adaptation – as compared to a science-first approach that focuses on the climate projections and impacts (as in CCRA1). The success of CCRA2 was particularly noteworthy given the much lower resources available than for CCRA1.

Alongside this there was also some analysis of the uptake and use of the CCRA2 Evidence Report in policy, i.e. in the subsequent five-year adaptation policy period and the 2<sup>nd</sup> National Adaptation Programme for England (Defra, 2018), as well as the Adaptation Programmes of the DAs. The CCC Adaptation Progress Report (CCC, 2019a), and supporting research (Watkiss et al., 2019) found that the coverage of the risks and opportunities from the CCRA2 Evidence Report in the 2<sup>nd</sup> NAP (Defra, 2018) was partial. A similar finding (Watkiss et al., 2019) was found for the use of CCRA2 Evidence material in the UK Government 25 Year Environment Plan (25 YEP) (HMG, 2018), which set out the long-term strategy for the environment, including climate change. For the latter, the analysis identified that there was not a systemic analysis to integrate climate risks across the 25YEP objectives and goals (i.e. a climate adaptation mainstreaming exercise).

CCRA2 undertook a very high-level assessment of the benefits of further action (step 3 of the method), consistent with the resources available. The reviews above identified that in many cases, this step identified future research priorities. A greater focus on potential interventions, rather than

research gaps, was therefore identified to offer more relevant information for the development of planned adaptation by the Government.

Finally, as noted above, after CCRA1 a number of formal evaluations were undertaken. This process step was not repeated in the same depth after CCRA2, reducing the opportunity for learning. A stronger component of evaluation and learning was therefore identified, to be undertaken after the publication of CCRA3.

## 2.2.2 Lessons from other national climate risk assessments and academic literature

The UK is not the only country undertaking climate risk assessments. Most European countries have undertaken these types of climate risk assessments and have published national adaptation plans, and globally, many countries are undertaking similar exercises as part of the UNFCCC National Adaptation Plan process. These other assessments provide potentially valuable lessons, and a rapid review of other national risk assessments was undertaken to help inform CCRA3. The review concentrated on those countries that have already undertaken multiple assessments (and thus include learning cycles). Some of the key findings are summarised in Box 2.2. The lessons from this review were used to update the CCRA3 method, so as to reflect current good practice (see section 2.3).

There are also other climate change risk assessments at different scales emerging in the UK, such as the recent climate risk and opportunity assessment for Glasgow City Region (CRC, 2019) and the analysis of the Climate Risk Assessment by Kent County Council on behalf of the Kent Climate Change Network. This highlights that national level assessments can cascade down to local risk assessment, either using similar approaches or assessing what the national level implications mean for the local area.

### **Box 2.2** Review of other Climate Change Risk Assessments.

A number of other national climate change risk assessments were rapidly reviewed. The focus was to identify additional methodological aspects as compared to CCRA2, and look for lessons on application in national risk assessment. Some key insights are highlighted below that were considered particularly relevant.

The US 4th National Climate Assessment (USGCRP, 2018) is a mandated risk assessment, which is delivered every four years, with the requirement to analyse the effects of global climate change (on the USA). The assessment is an extremely comprehensive analysis, and has benefited from several successive assessment cycles. It provides some useful lessons on how to raise interest in climate risks in a challenging climate policy landscape. Methodologically, it has many aspects that are similar to CCRA, but the most recent analysis also refined the goal to focus on key messages using a series of questions:

- What do we value? What is at risk?
- What outcomes do we wish to avoid with respect to these valued things?
- What do we expect to happen in the absence of adaptive action and/or mitigation?
- How bad could things plausibly get?
- Are there important thresholds or tipping points in the unique context of a given region, sector, and so on?

The aim was to address the overarching question of ‘what keeps you up at night?’ There was also a stronger focus on:

- Impacts and losses on the economy;
- Extreme impacts (Impacts from changes in extreme statistics of key climate variables) that are less likely but have severe consequences;
- Communicating cascading effects among and within complex systems;
- Quantification of risks that could be avoided by taking action.

The Netherlands has been one of the leaders in climate risk and adaptation planning globally. The most recent National Climate Adaptation Strategy 2016 (NAS, 2016), while it has different objectives to the UK CCRA, does include a risk assessment and this uses four diagrams (‘Hotter’, ‘Wetter’, ‘Drier’ and ‘Rising Sea Level’) to visualize the effects of climate change within nine sectors: water and spatial management; nature; agriculture, horticulture and fisheries; health and welfare; recreation and tourism; infrastructure (road, rail, water and aviation); energy; IT and telecommunications; public safety and security. From this it sets out six climate effects which call for immediate action to be identified. The diagrams provide a useful way of trying to communicate climate information and have been reviewed alongside other international examples to help design the CCRA3 summary products.

There is also a literature on climate change risk assessment associated with the large flows of finance being spent internationally on adaptation, which provides valuable new insights. In 2017/18, global public finance flows for adaptation were estimated at US\$30 billion (CPI 2019). A very large proportion of this (\$7.4 billion: MDBs, 2017) was financed by the large multi-lateral development banks (MDBs) and International Financial Institutions (IFIs) including those in Europe. Of high relevance, these organisations have implemented climate risk management systems (CRMs) as part of their due diligence processes, and they undertake routine climate change risk assessment of investments, especially for infrastructure (MDBs, 2017). These assess the level of climate risk during the project appraisal cycle, and if needed, include adaptation (resilience) measures. They provide an existing and applied evidence base on processes and implementation practice for climate risk analysis of major investments, as well as lessons on improving risk assessments over time (ADB, 2020) that have relevance for national assessments.

The academic literature on climate risk assessment and adaptation has also developed considerably since the last CCRA. A rapid review to inform CCRA3 identified a number of relevant themes that were subsequently incorporated where possible into the CCRA3 method:

- A greater focus was included to encourage iterative risk management (Jones et al., 2014) in CCRA3 (also called adaptive management), to help prioritise and sequence adaptation over time. These approaches are sometimes called adaptation pathways, though this term is used for several different approaches (see key terms Box 2.1).
- The lessons from new decision support approaches for adaptation, including decision making under uncertainty (DMUU), were included in CCRA3. While most of the formal DMUU methods are more applicable at the project scale, rather than at the national level, the concepts that these approaches advance, e.g. robustness, diversity, flexibility, learning, and minimizing regret (Watkiss et al., 2014), are useful to help identify potential additional adaptation action.
- An additional method component (in Step 2 on adaptation) was added to recognise that there are barriers (constraints) to adaptation (for both risks and opportunities) (Klein et al., 2014), and

that addressing these barriers is important for implementation of adaptation. This also aligns to the traditional policy appraisal framework in UK Government (set out in the UK Green Book, HMT, 2018), and can help the subsequent justification for adaptation policy and programming.

- There was a greater focus on the consideration of climate risks in private sector decisions in CCRA3, reflecting developments on the financial reporting of climate risks. This aligns to the initiatives of the Task Force on Climate-related Financial Disclosures (TCFD, 2017) and the Network for Greening the Financial System (NGFS, 2019). These frameworks identify physical climate risks (the risks which are the focus of CCRA3) as well as transition risks (associated with policy or technology change as the world reduces greenhouse gas emissions, which are not considered in CCRA3). There has also been a recent recognition of liability risks, which arise from people or businesses seeking compensation for losses they may have suffered from physical or transition risks (BoE, 2018). These initiatives are likely to stimulate greater interest from the private sector in the CCRA3 results. In response, the CCRA3 Expert Advisory Panel strengthened private sector involvement and interest in CCRA3, though the main audience for the Independent Assessment (including the Technical Report) remains Government.
- Reflecting the government request, the CCRA3 method considered, in indicative terms, the monetary valuation of risks and opportunities (presented in a separate economic report), and the indicative costs and benefits of further adaptation (included in Step 3).
- The CCRA3 method and its implementation have also adopted a stronger emphasis on co-design and co-production - i.e. the participatory development of the project with stakeholders (end-users) (Hegger et al., 2012; Beier et al., 2016) than previous cycles. This drew on recent review work which has identified the key success factors for co-production for climate change and adaptation (COACCH, 2018). Additional co-production activities were undertaken as part of the Technical Report chapter research and analysis, while noting there were some limits due to the need to respect the governance arrangements for CCRA3, i.e. to produce a report that is independent of Government while at the same time undertaking co-production of research with Government as a key end-user.
- There is growing recognition that climate risks will not be distributed evenly (among groups as well as places) (JRF, 2016) and thus additional consideration of distributional effects and inequalities was included.
- There is more focus on the potential synergies and trade-offs between adaptation and mitigation (OECD, 2017; IPCC, 2018a), and this became even more relevant area during the time-period of CCRA3 with the announcement of Net Zero targets and analysis (CCC, 2019b).
- Finally, there is a growing focus in the literature on the need for transformational adaptation (Field et al., 2014; Lonsdale et al., 2015; CRC, 2020), which requires fundamental change, as compared to incremental adaptation (see Box 2.1) and this is reflected in the final method step and greater linkages to CCRA4.

### 2.2.3 New Climate Science and UKCP18

A new, comprehensive set of state-of-the-art climate projections for the UK were released in November 2018 by the Met Office and its partners (Lowe et al., 2018; Murphy et al., 2018; Palmer et al., 2018), commissioned by Defra. The UKCP18 projections provided important new information of relevance to CCRA3 and were taken into account as much as was practically possible. For example, they were used in the supplementary analysis undertaken by the research projects.

A key part of the CCRA3 methodology was to take advantage of the new UKCP18 information, while acknowledging that due to the timing of release, it has not fed into the risk and opportunity literature. Reflecting this, the Technical Report has drawn on scenarios and studies that are not based on UKCP18 in order to ensure evidence is drawn from the widest possible base of research.

Although a number of studies have already been carried out using UKCP18, most of the literature on future UK climate risks assessed in CCRA3 is inevitably based on the previous set of climate projections, UKCP09 (Murphy et al., 2009). It is noted that some climate risk-related quantities in UKCP18 are quite different to those in the previous projections, while others are similar (see Chapter 1: Slingo, 2021). It has been important to assess where these differences are extensive enough to affect the advice previously provided by the CCRA, and thus affect CCRA3 findings.

UKCP18 contains some projection tools that are similar in nature to those in UKCP09, such as the probabilistic projections, the regional climate model projections and the sea-level rise projections. As an update from UKCP09, UKCP18 includes the more recent emissions scenarios linked to the Representative Concentration Pathways (RCPs). The probabilistic projections considered four RCP scenarios, ranging from RCP2.6 (which is consistent with extensive mitigation of emissions) through to RCP 8.5 (which has future emissions considerably higher than pathways considered consistent with current worldwide energy policies). The intermediate scenarios RCP4.5 and RCP6.0 were also included: these are within the range of possible emissions futures considered consistent with current worldwide policies, and RCP6.0 is used to define the higher climate change scenario used in the CCRA3 Technical Report (see Box 2.5 and also the Introduction chapter: Betts and Brown, 2021).

An important feature of both the UKCP18 and UKCP09 probabilistic projections that is different to most other projections with General Circulation Models of climate is that they are driven by scenarios of emissions scenarios rather than concentrations. For example, the widely-used models in the 5<sup>th</sup> Coupled Model Intercomparison Project (CMIP5) apply the RCPs as pathways of greenhouse gas concentrations in the atmosphere, but in contrast, UKCP18 uses emissions scenarios aligned to the RCPs but calculates its own concentration pathways accounting for uncertainties in carbon cycle feedbacks to be explored and quantified. The latter approach results in a range of concentration pathways, most of which rise faster than the standard RCP concentration pathways. This is an important influence on the differences in projected rates of warming between UKCP18 and CMIP5 (Murphy et al., 2018).

As a further advance from UKCP09, information from the UKCP18 probabilistic scenarios has been used to quantify the effects of natural climate variability on the spread of future outcomes (Murphy et al., 2018).

As well as the UK and global probabilistic projections, UKCP18 provided a 28-member perturbed parameter ensemble (PPE) of global (60km resolution), and PPEs of regional (12km) and local (2.2km) projections over UK land areas, driven by a range of concentration pathways arising from the standard RCP8.5 emissions scenario. The 12km resolution of the regional projections is higher than the 50 km resolution of the equivalent projections in UKCP09, and in some cases these project larger changes in weather extremes such as heavy precipitation – a comparison of this was carried out in support of the CRA3 Technical Report (Johns et al., 2021). The high-resolution (2.2km) Convective Permitting Model used in the local projections has been shown to simulate extreme

precipitation events more realistically than lower-resolution models so the changes in the local projections provide further important context for the assessment, as discussed in Chapter 1.

60km-resolution projections were also provided for global warming levels of 2°C and 4°C global warming above pre-industrial, and for the RCP2.6 emissions scenario (Gohar et al., 2018).

UKCP18 also includes probabilistic projections with one of the same emissions scenarios (SRES A1B) as used in UKCP09, so that a direct comparison can be made with previous probabilistic projections (Murphy et al., 2018). The method used for assessing the implications of the new regional climate projections in the UKCP18 projections for conclusions derived from UKCP09-based regional projections is described in Box 2.4.

Like UKCP09, UKCP18 also includes marine projections including the rise in long-term average sea level, changes in short-term extreme water levels from storm surges, and changes in wave height (Palmer et al., 2018). Since these were developed in parallel with the new climate modelling system used for the UKCP18 land projections, the marine projections used existing climate projections from CMIP5. Although this inevitably results in potential inconsistencies between the UKCP18 land and marine projections, this does not pose a difficulty for CCRA3 as the Technical Report already draws on literature from a wide range of very different sources and has applied a framing of future projections which groups these together appropriately.

## 2.2.4 New climate science: low-likelihood, high-impact scenarios and events

It is important for a risk assessment to consider high-impact outcomes even if they are considered to be of low likelihood. This includes responses of the climate system outside of the ranges considered “likely”, and also potential abrupt climate changes and the passing of “tipping points” in the Earth System (see Chapter 1: Slingo, 2021). Examples of the former include high values of equilibrium climate sensitivity or carbon cycle feedbacks strength which are facilitated by the use of probabilistic projections. Regarding climate tipping points, also known as earth-system tipping points, and sometimes as climate tipping elements (Lenton et al., 2008; Lenton et al., 2019), some of these are now included in mainstream climate projections and other studies related to these, but many are still not.). Nevertheless, they are increasingly recognised as a very important component of climate change risk assessment, and modelling and theoretical work has been performed to explore them outside of the mainstream climate projections.

These earth system climate tipping points elements were not included in depth in CCRA1 or CCRA2, and this was considered an important omission. They have therefore been included in CCRA3. Some are included either explicitly or implicitly in the UKCP18 projections: the marine report considers the implications of marine ice shelf instabilities which could lead to more rapid sea level rise, and the probabilistic land projections include uncertainties in carbon cycle feedbacks based on a model which simulates die-back of the Amazon forest in some of its simulations (Boulton et al., 2017). The high-emissions RCP8.5 scenario can also serve as a proxy for climate projections with much stronger carbon cycle feedbacks than in current Earth System Models, which could be used to represent the effects of permafrost thawing and other biospheric sources of carbon dioxide or methane emissions. A scenario of shutdown of the Atlantic Meridional Overturning Circulation (AMOC) has also been examined with a version of the main climate model used in UKCP18 (Jackson et al., 2015), and although this is not included in the UKCP18 projections themselves, it has been used for assessing

some impacts on the UK (Ritchie et al., 2020). The implications of some of these has been considered for a limited number of risks, and an additional study was performed for CCRA3 to examine these and other tipping points from a UK perspective (Hanlon et al., 2021). Since this showed that information on the implications of other climate tipping points for UK climate risks remains limited, it was not possible to include an assessment of tipping points at the level of all individual risks and opportunities. Instead, they are considered through a separate cross-cutting analysis in each chapter following the discussion set out in Chapter 1 (Slingo, 2021).

## 2.2.5 Additional Commissioned Research

Following the CCRA2 Evidence report, an evidence gap analysis was commissioned by the CCC. This identified over 200 evidence gaps. Following a stakeholder engagement period in 2016 – 2018, the CCC commissioned six research projects to inform the CCRA3 Technical Report, using funding provided by Defra, the devolved administrations and research councils (NERC, ESRC and EPSRC). These projects were:

1. Updated projections of future water availability for the UK (HRW, 2020);
2. Updated projections of future flood risk for the UK (Sayers et al., 2020);
3. Understanding how behaviours can influence climate change risks (Power et al., 2020);
4. Climate driven threshold effects in the natural environment (Jones et al., 2020);
5. Interacting risks (WSP, 2020);
6. A consistent set of socioeconomic projections dimensions for the CCRA3 Evidence Report research projects (Cambridge Econometrics, 2019).

These projects have fed into CCRA3 in a number of ways. The flood risk and water availability studies provided updated quantified risk estimates for CCRA3, using the new UKCP18 products. They also used the new socio-economic projections provided by the sixth research project. Some of the other studies have provided information of relevance to the update methodology in CCRA3. The threshold study helped to provide information for the new pathways thinking in CCRA3, while the interacting risks project was used to help assess the interacting and cross-cutting risks (which are undertaken for each risk/opportunity in the chapters in CCRA3, rather than as a separate cross-cutting chapter as in CCRA2).

Work was also commissioned in support of the CCRA3 Technical Chapters to assess the impacts of climate change on agricultural land use and associated greenhouse gas emissions (Mancini et al., 2021), again using UKCP18 projections. Further additional work was carried out by the research community on implications of climate change for wildfire risks in the UK (Belcher et al., 2021). This had been identified as an area where the evidence base had not advanced substantially between CCRA1 and CCRA2.

The results of these studies and the CCRA3 research described in sections 2.2.3 and 2.2.4 are included throughout the Technical Report chapters and referenced as such.

## 2.3 The CCRA3 Approach: Using Risk Assessment to Inform Adaptation

### 2.3.1 The Framework for CCRA3

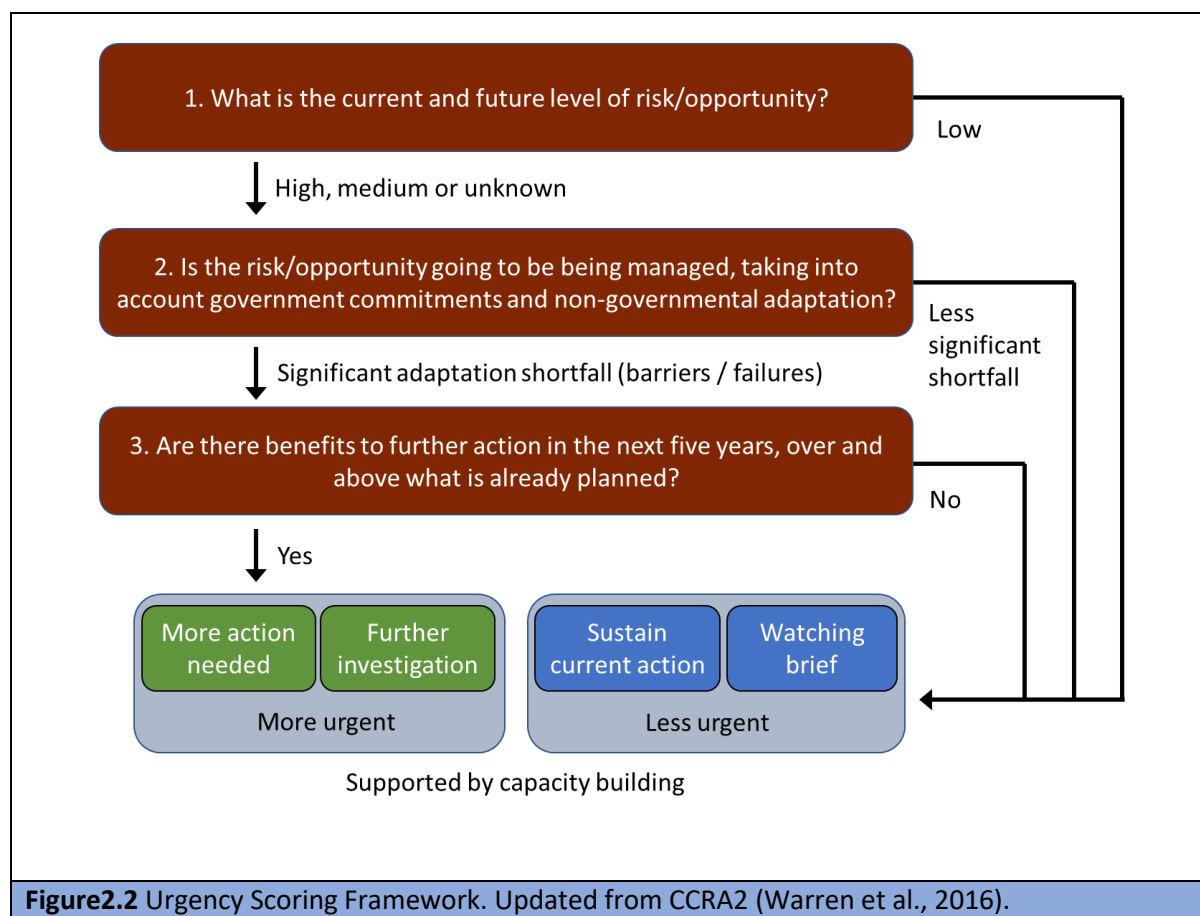
The CCRA3 Evidence method is based on the prioritisation of risks and opportunities, using an analysis of urgency. This seeks to address the issue of ‘where is action needed most urgently over the next five-year period’? This is complemented by a second framework (applied in Step 3) that helps to identify early adaptation priorities to respond to the identified risks and opportunities, i.e. that seeks to address the issue of ‘what type of action is most urgently needed?’

#### 2.3.1.1 Establishing urgency

The analysis of the urgency of risks and opportunities was undertaken in CCRA2 through an urgency framework (Warren et al., 2016). This high-level framework has been carried over into CCRA3, with minor refinements. It prioritises risks and opportunities using three questions:

1. What is the current and future level of risk/opportunity?
2. Is the risk/opportunity going to be managed, taking into account Government commitments and other non-Government adaptation?
3. Are there benefits to further action in the next five years, over and above what is already planned?

These three questions are shown within the decision flow diagram in Figure 2.2.



#### 2.3.1.2 Identifying possible priorities for early adaptation

The CCRA Technical Report aims to provide evidence to inform adaptation. Following from the urgency diagram above, it seeks to provide additional information on what type of adaptation action



might be beneficial in a case where more action is needed. This is influenced by the type of decision, noting that for many risks and adaptation responses, there is a need to address the challenge of deep uncertainty, i.e. where the probability of risks is not known (Hallegatte et al., 2012). An initial adaptation framework was set out in CCRA2 (Warren et al., 2016; Warren et al., 2018). This built on a well-established literature and existing frameworks for identifying early adaptation priorities, using a portfolio or ‘building block’ approach (drawing on Fankhauser et al. (1999); Ranger et al. (2010); Watkiss and Hunt (2011)). This framework has been updated in CCRA3, and identifies three main priorities for early adaptation activities, which are to:

- Address any current adaptation gap by implementing ‘no-regret’ or ‘low-regret’ actions<sup>1</sup> to reduce risks associated with current climate variability as well as building future climate resilience, or to enhance opportunities.
- Intervene to ensure that adaptation is considered in near-term decisions that have long lifetimes, such as major infrastructure developments, in order to avoid ‘lock-in’ (see key terms). This can include the use of decision making under uncertainty (DMUU) concepts (i.e. flexibility, robustness).
- Fast-track early adaptive management activities, especially for decisions that have long lead times or involve major future change, including planning, monitoring and research. This can enhance learning and allows the use of evidence in forthcoming future decisions, for either risks or opportunities.

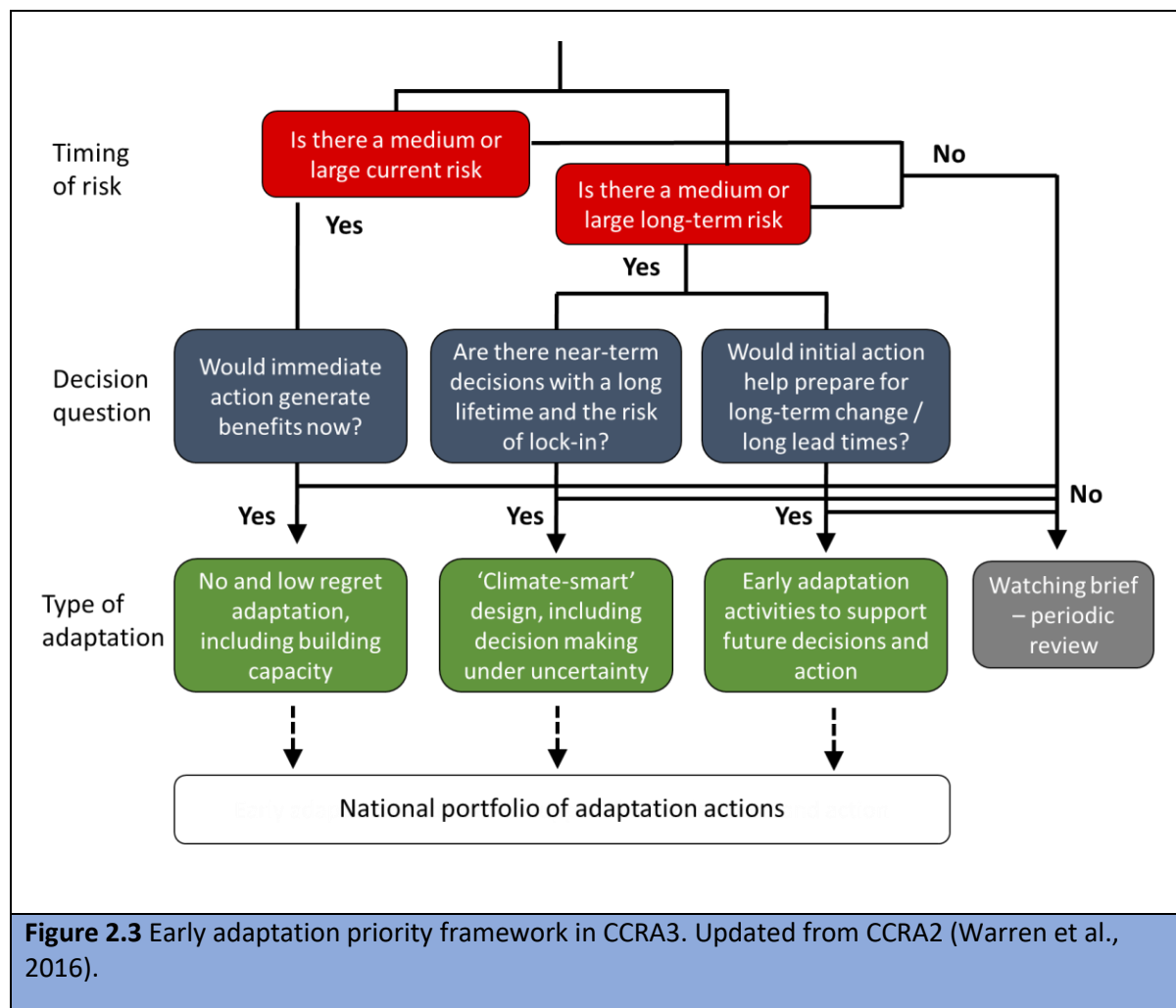
These are shown in the adaptation priority framework in Figure 2.3, along with the decision characteristics involved. It is stressed that at the national level, all three of these adaptation priorities or building blocks (shown in the green boxes) are needed, and this requires portfolios of interventions for each individual risk or opportunity. Indeed, the three activities above can be part of an overall adaptive management process or adaptation roadmap (see section 2.3.2).

The differences between the three ‘building blocks’ of early adaptation in Figure 2.3 are quite subtle, but important. Each involves a different combination of the time-scale of climate risks and the time period of the adaptation decision. On the left of Figure 2.3, there are some current decisions or actions that can be taken now to address current climate risks. These lead to an immediate benefit. An example is to improve weather and climate services to reduce current weather-related impacts from heatwaves. Moving to the centre of Figure 2.3, there are some near-term decisions which will be exposed to future climate change risks, and there is a one-off opportunity to adapt now. For example, to change the design of a major new infrastructure project (e.g. a major bridge or hydroelectric-power plant) to make them more resilient to future climate change, noting later major retrofits could be expensive or impossible. Finally, on the right of Figure 2.3, there are some future decisions that may need to be implemented to address major climate change in the future. Some of these will take time to develop, and some will benefit from improved information and learning. In these cases, it makes sense to start planning now (especially if lead times are long or the potential for learning is large). The Thames Estuary 2100 project (Ranger et al., 2013) is such an example,

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<sup>1</sup> No-regret adaptation is defined as options that ‘generate net social and/or economic benefits irrespective of whether or not anthropogenic climate change occurs’ (IPCC, 2014b). A variation of no-regret options are win-win options, which are options that have positive co-benefits, which could include wider social, environmental or ancillary benefits. These are differentiated from low-regret options, which may have low costs or high benefits, or low levels of regret, or may be no-regret options that have opportunity or transaction costs in practice.

where early planning and monitoring has been put in place now to prepare for the possibility that a new Thames Barrier might be needed in the long-term. The key point is that all of these involve some actions in the next five years, i.e. in the next NAP period.



This adaptation framework is applied in Step 3 of the urgency method (see Figure 2.2). However, a lesson from the review of CCRA2 was that this requires particular evidence to be gathered in Steps 1 and 2, to allow the subsequent application of the framework in Step 3. For this reason, additional information requirements (to inform adaptation) were added early in the CCRA3 method - this includes a greater emphasis on lock-in, thresholds, and adaptive management – and are discussed in the next section.

It is noted that while this methodology has been applied to all risks and opportunities in CCRA3, it is more challenging to apply this approach to international risks (Chapter 7: Challinor and Benton, 2021). Additional information on how this has been addressed is presented in that chapter.

This method was applied to all risks and opportunities, at the level of each of the four countries (England, Northern Ireland, Scotland and Wales) as set out in the CCRA3 Requirement Document. It is highlighted, however, that risks and opportunities vary across regions and populations. In practice, for adaptation decisions, greater dis-aggregation may be needed.

### 2.3.2 New focus areas in CCRA3

A number of additional developments – related to the frameworks above - are included in CCRA3. These encourage more adaptive management thinking in the CCRA, although there are limits to what is possible given that CCRA3 is a synthesis exercise, rather than new analysis of future impacts and adaptation. These are described briefly below.

#### 2.3.2.1 Risks of Lock-in

The first area that is given greater weight in CCRA3 is the risk of **lock-in**. The adaptation literature on lock-in has generally focused on decisions that ‘lock-in’ the potential for future climate change risks that are difficult or costly to reverse or change later (Fankhauser et al., 1999; Ranger et al., 2010; Fankhauser et al., 2013) and this term was included in CCRA2 (Warren et al., 2016). It is recognized that lock-in is an important issue for early action, and it has been considered in recent CCC progress reports (e.g. CCC, 2015; 2017; 2019a). The term lock-in has also appeared in the IPCC glossary for recent special reports (IPCC, 2018b), which defines it as *a situation in which the future development of a system, including infrastructure, technologies, investments, institutions, and behavioural norms, is determined or constrained (‘locked in’) by historic developments*. CCRA3 investigated these issues in more detail, with an updated literature review on lock-in, including a consideration of the use of the term in the mitigation literature (see Seto et al., 2016).

Based on this, a new definition was developed for the CCRA3 (see Box 2.1). This captures the relevant focus on lock-in that could arise in the next NAP period (i.e. the next five years or so) and relates to actions or decisions that could potentially increase future risk or vulnerability and that are also difficult or costly to reverse later (quasi-irreversibility / path dependency). This can be from i) action or decision taken that is business-as-usual’, ii) from a lack of an action or decision, or iii) from a maladaptive action or decision.

An example where business-as-usual actions or decisions could involve lock-in (i) is the building of new infrastructure, which has a long life-time. Where this does not consider future climate risks, this may experience large future climate impacts, and/or could be expensive or difficult to retrofit later. This could be large projects that do not consider future floods risks or building large numbers of houses that do not consider future overheating risk. It can also involve land-use decisions, as these tend to lock-in development patterns irreversibly, e.g. developing new areas that may become at risk under future climate related flooding. At the same time, lock-in could also include policy decisions associated with these investments (e.g. building standards or development policy) and even new policy or market based instruments that increase exposure, sensitivity or vulnerability. An example of (ii) could include a case where peatlands are not restored in the short-term, leading to further degradation that is irreversible, which removes its coping capacity to future climate shocks. It could also include a failure to manage other drivers of stresses, such as rising demand for water, that increase susceptibility to future climate change. Finally, examples of maladaptation (iii) could include a major investment today that involves a sunk cost for an adaptation measure that may not be needed, or implementing costly adaptation without considering uncertainty (noting also that lock-in may constrain future adaptation decisions). In the CCRA3 method, a decision that involves a potential risk of lock-in is given a higher magnitude score, and assigned a higher urgency score requiring action sooner.

### 2.3.2.2 Thresholds

The second area of greater focus in CCRA3 is around **thresholds**. These represent levels or states beyond which there is step-change in risks and which may necessitate much greater levels of adaptation (or even may reach the limits of adaptation, Klein et al., 2014). This draws on the literature on adaptation decision-making under uncertainty (DMUU) and adaptation pathways (e.g. Ranger et al., 2013; Dittrich et al., 2016). CCRA3 has included more adaptive management thinking, with a more explicit consideration of thresholds and the potential differences for these between 2 and 4°C pathways. In considering these elements, authors were asked to consider a number of different types of thresholds:

- **Biophysical thresholds.** Typical examples are the suitability or lethal threshold limits for crops, temperature thresholds for heat and daily mortality, or thresholds for heating or cooling demand. These thresholds are sometimes translated into current policy, e.g. the Heat Health Watch heat-wave temperature thresholds, or occupational temperature thresholds.
- **Engineering thresholds.** These are often associated with design standards and tolerance levels for various climate parameters, e.g. rail buckling temperature thresholds, maximum water flows for drainage channels etc.
- **Performance thresholds.** These thresholds are linked to the adaptation tipping points literature (also known as adaptation turning points) (Haasnoot et al., 2013; Werners et al., 2013), and they relate to points beyond which a particular action is no longer adequate for meeting a plan's objectives and a different adaptation option or strategy is required, including sometimes more transformational measures. These can include a wide range of types of thresholds, e.g. service levels, economic returns.
- **Policy thresholds.** These may be policy levels that are set to politically determined levels of acceptable risk or economic optimality, e.g. the use of 1 in 100 year level of flood protection, or policies that define unacceptable risks.

It is noted that for the first of these, there may be natural or intrinsic thresholds, which may be immutable. For the other three, these thresholds are often set by decision makers, and thus reflect policy choices.

The consideration of thresholds (particularly performance thresholds) has been used widely in the adaptation tipping points literature and adaptation pathways (see definition Box 2.1). However, these pathway approaches and threshold analysis are more often used at the project level, and there are challenges to implement them at the national level. Nonetheless, there is a value to exploring potential risk (or opportunity) thresholds, to help inform the CCRA3 and to encourage more pathway thinking. It is also highlighted that there is a separate literature on global (Earth System) thresholds (often called climate tipping points), discussed in section 2.6., which should not be confused with the thresholds or adaptation turning points discussed above.

### 2.3.2.3 Sequencing adaptation, adaptive management and transformational adaptation

While the focus of CCRA3 is to identify where further adaptation is needed in the next reporting period (to address priority risks and opportunities over the short, medium and long-term), these early priorities need to be seen as part of a longer-term **adaptive management process**, i.e. that encourages a cycle of evaluation, learning, and revision (of possible actions).

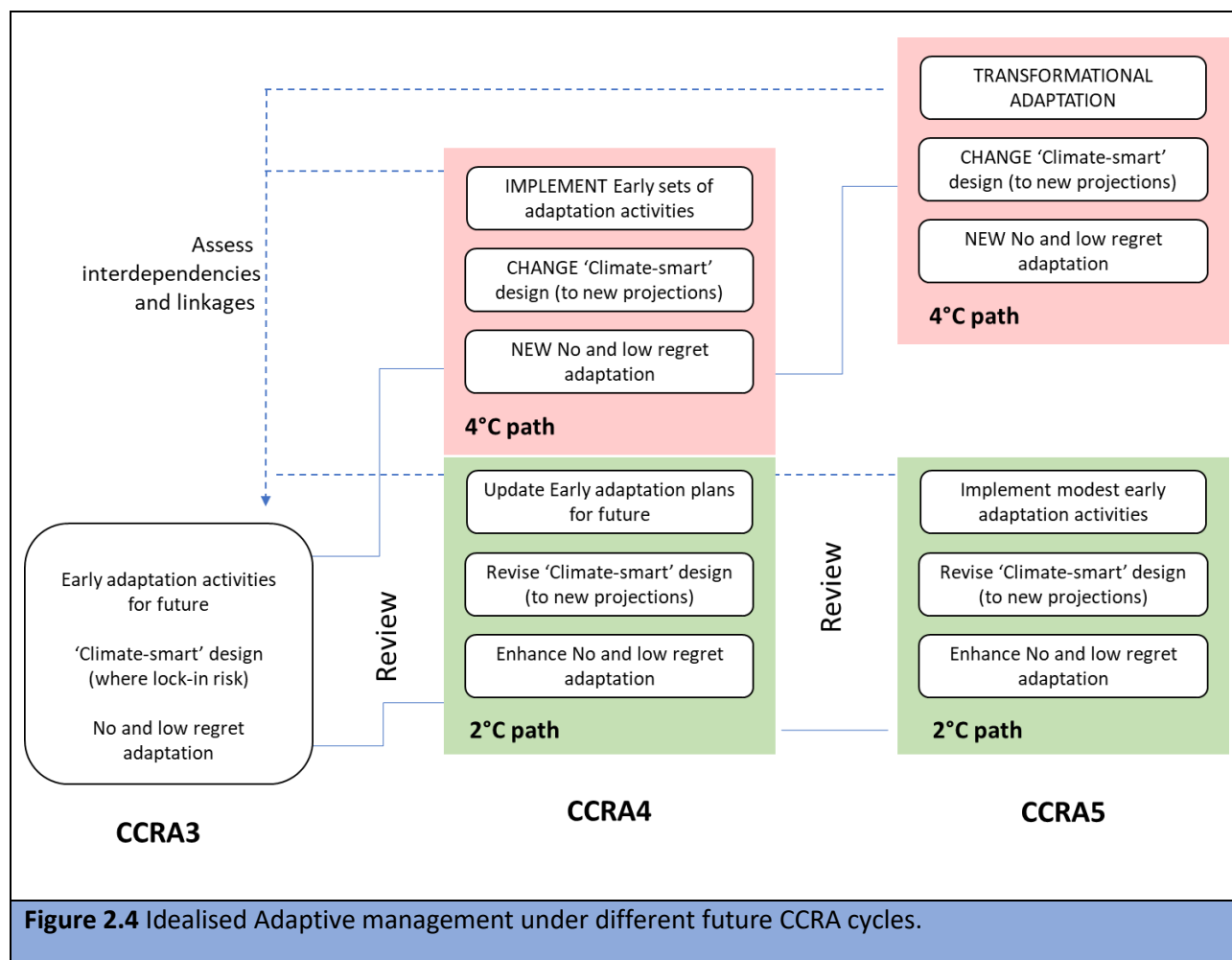
CCRA3 therefore includes more emphasis on iterative adaptive management. The aim is to encourage more consideration of risks and opportunities – and adaptation - over time and across scenarios (including uncertainty). This is particularly important because of the regular repeat cycle of the CCRA process every five years, and thus the opportunity to learn and update over time.

In the national context, this could extend to adaptation roadmaps, i.e. generic adaptation pathways. These are not to be confused with detailed dynamic adaptation route-maps, which are a decision support method used primarily at the project level (e.g. as in Thames Estuary 2100, see Reeder and Ranger, 2013), which are often called dynamic adaptation pathways (see Box 2.1).

However, while an adaptive management process is inherent in the CCRA and NAP process due to the five-year repeat cycle, operationalising this in practice is very challenging at the national scale. There are some examples, notably in the Netherlands with the Delta Committee and plans (Marcel et al., 2011) but these tend to focus on sea-level rise, which lends itself more easily to such analysis. Following the CCRA1, Defra funded an Economics of Climate Resilience study (Frontier Economics et al., 2013; HMG, 2013) which developed national level adaptation roadmaps. While this approach was informative, and identified actions over time (for successive CCRA cycles), it was found to be difficult to implement the findings at the sectoral level, because there are multiple risks (and opportunities). This indicates adaptive management (roadmaps) is more applicable at the level of individual risks or opportunities. However, developing a national adaptation roadmap for every CCRA3 risk and opportunity would be a major undertaking and has not been possible given the resources available and synthesis nature of CCRA3. Nonetheless, recent national level analysis (for the CCC) did develop indicative analysis for ten specific risks and opportunities (Watkiss et al., 2019) and found it was possible to identify lock-in and thresholds, and to include some general suggestions on moving to an adaptive management approach. CCRA3 authors were therefore asked to try and incorporate a similar discussion in Step 3 of the CCRA method, i.e. to try and consider some of the implications of lock-in and thresholds, as well as to include adaptive management suggestions for further action.

Looking forward, it would be useful to maximize the linkages between successive CCRAs (see Figure 2.4) to try and encourage a more formal iterative approach into national risk assessment. As a first step towards such an approach, CCRA3 included an additional question for authors to address in the analysis on ‘what evidence or learning would help to inform CCRA4?’

This recognises that the CCRA4, which is due for completion in 2027, will inform the fourth NAP and DA adaptation programmes for the period 2028-2032. By this time, the UK’s climate is projected to be significantly different as compared to the last century, and could be entering a period of very major climate change in the decade that follows, especially if global international mitigation efforts are below the levels needed to deliver the Paris Agreement. Therefore, authors were asked to consider what additional information might be useful to help inform CCRA4 and NAP4 decisions and they were also asked to explicitly consider where transformational adaptation might be needed.



## 2.4. CCRA3 Process

### 2.4.1 Overview of the CCRA3 Process

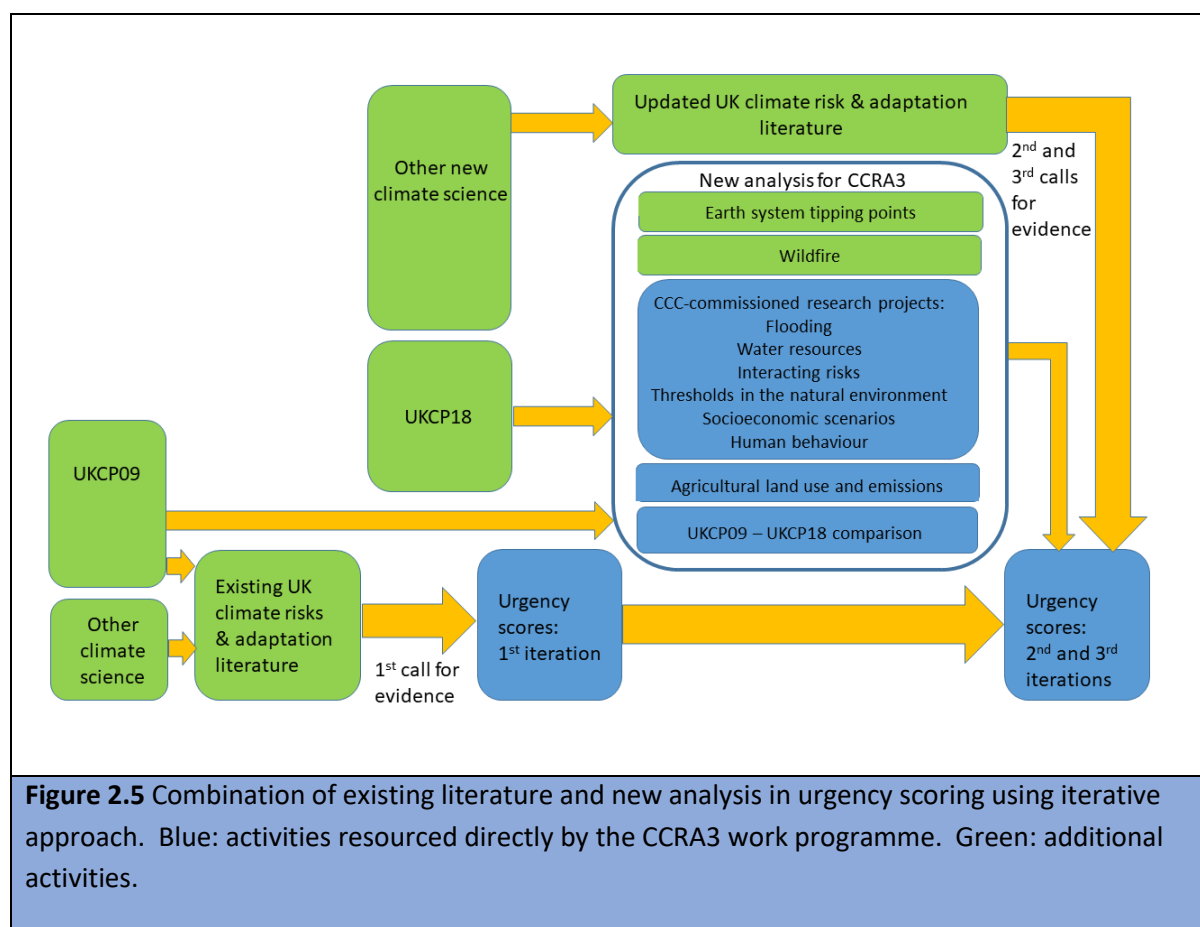
This section sets out the process involved in the development of the CCRA3 method. Building on the CCC method statement, as well as the early review work (on other national risk assessments and the academic literature), a first draft of the CCRA3 Technical Report Methodology Paper was produced in April 2019. This was reviewed internally by the CCRA3 Technical Report team and by the CCC secretariat. Following updates, a second draft of the method paper was produced and was shared with the Chapter teams for discussion, and a methodology workshop was held with this group in May 2019. The resulting changes and updates were used to produce a third version, which was reviewed by an external Expert Advisory Panel (EAP, in June 2019) and presented to the CCRA3 Project Board for comment (July 2019). The comments received were used to produce an updated version of the methodology, which went out for detailed external peer review during August and September 2019. This included review by the Government, the EAP and the external peer review panels. A large number of comments were received from this review, and these were used to produce a fifth version of the methodology chapter (along with a logged response to all 350 comments).

This version was used by Chapter teams for the first round of the CCRA Evidence analysis and urgency scoring. The methodology was operationalised through the development of a CCRA3 Risk/Opportunity template, which set out the questions that chapter teams should address (and record) for each of the three urgency method steps, along with worked examples. The template is attached in Annex 1. To support this process, a slide presentation pack on ‘how to’ implement the method was produced.

During the autumn of 2019, a number of activities (method authors or working groups) further developed the methodology. This included consideration of socio-economic scenarios including the UK Net Zero target, adaptation pathways, interacting and cross-cutting risks and equity/distributional impacts. A revised methodology chapter was produced in January 2020, along with an updated template, and discussed at a CCRA3 meeting with the chapter teams in February 2020. This was finalised for the second round of CCRA Evidence analysis in March 2020, and was also sent out for a final peer review in May 2020 by the Government, the EAP and the external peer review panel. The comments from this review were used to produce a draft final version of the methodology chapter in October 2020, which was circulated with other chapters for a final round of peer review in November 2020, but with instructions for comments to focus on updates only.

## 2.4.2 Overview of the CCRA3 Evidence Process

The CCRA3 method was applied using a three-round approach to derive the magnitude and urgency scores. This iterative process is set out in Figure 2.5.



The initial pass of the urgency scores was undertaken during late 2019, based on existing literature. A second iteration of the urgency scores was made in early 2020, following the evidence from the UKCP09-UKCP18 comparison, the outputs of CCRA3 research projects, the outputs of CCRA3-focussed research in other programmes, and new literature published later in the CCRA3 analysis and writing period. A final iteration was made in late 2020 to ensure an up-to-date assessment reflecting the latest literature.

## 2.5. CCRA3 Method Overview

The final methodology is summarised in Figure 2.6, showing the **three urgency steps** (in red) and associated questions, along with the **tasks** (in blue) that are undertaken at each of these steps. This is presented as a flow chart, which shows how the evidence at each stage progresses through towards the analysis of urgency. The key outcomes are shown in green, and include the magnitude scores (Step 1) and the urgency scores (Step 3).

The method is designed to treat evidence consistently, irrespective of the sector or system affected, creating a balanced assessment representative of the available literature. The three steps are briefly described below and then outlined in detail in the subsequent sections.



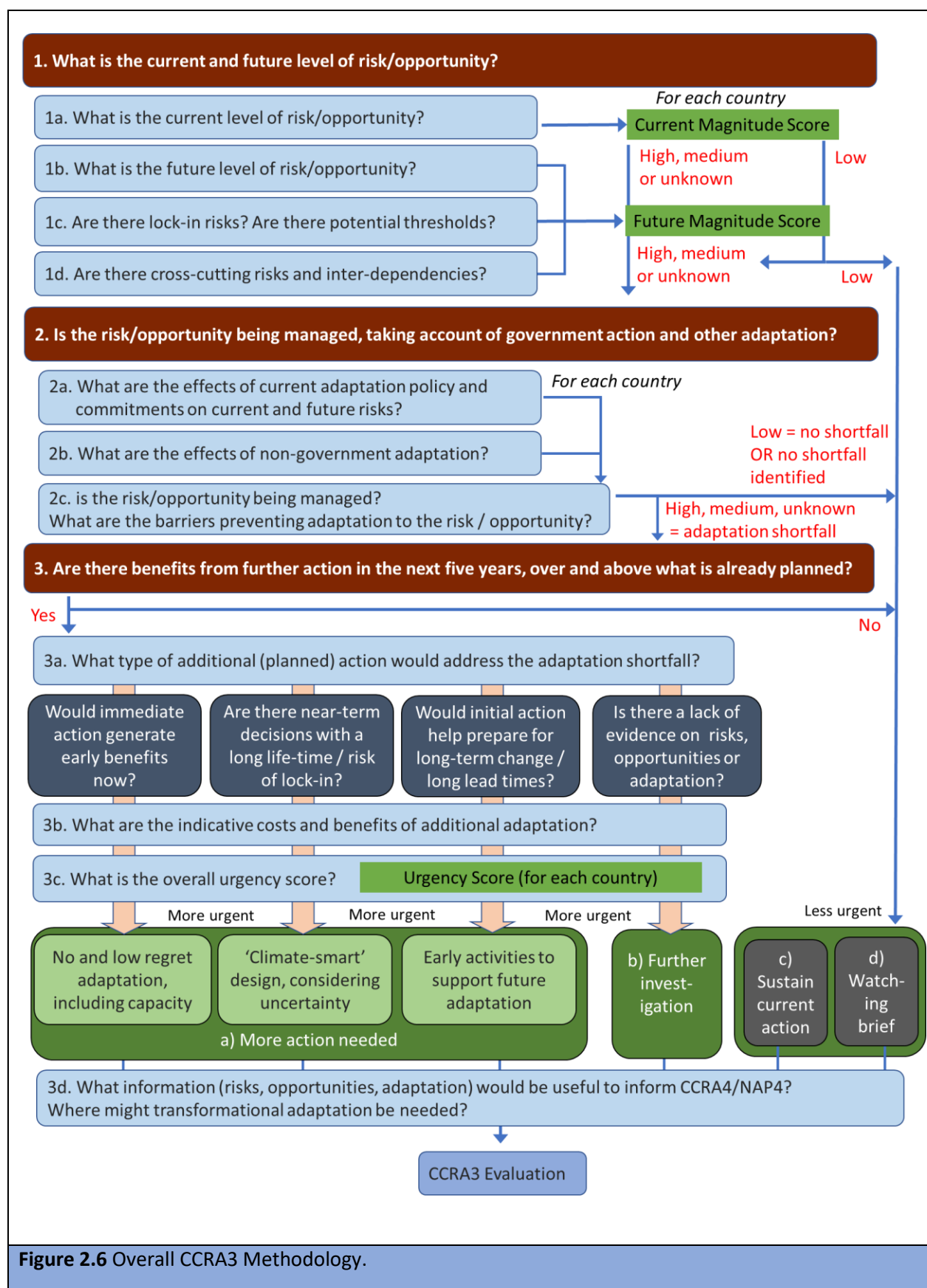


Figure 2.6 Overall CCRA3 Methodology.

### 2.5.1 Step 1: Assessment of risks and opportunities

This step undertakes the analysis of current and potential risks and opportunities, and undertakes an initial scoring of their magnitude. It is stressed this scoring is undertaken at the national level, i.e. individually for all four countries. This first step includes the following tasks:

**Step 1a. Current risks and opportunities.** This task sets out to understand and assess present-day current climate-related risks and opportunities, with a quantitative or qualitative assessment of their magnitude (see magnitude scoring Tables 2.2 and 2.3). For risks, it assesses how vulnerability, exposure and hazards affect current risks, including the influence of socio-economic drivers. For opportunities, as the IPCC hazard-exposure-vulnerability framework does not apply, the focus is on understanding the current influence of climate. This task also considers the distributional effects and potential inequalities associated with risks and opportunities. An analysis of the magnitude for risks and opportunities is made (individually) for each of the four countries (England, Northern Ireland, Scotland and Wales) (see Table 2.2 and 2.3, below), along with an analysis of the confidence in this score, based on the quality of the evidence and the level of agreement in the evidence between studies and authors (see Tables 2.4 and 2.5).

**Step 1b. Future risks and opportunities.** This task extends the analysis above to understand and assess how climate and socio-economic change may alter risks and opportunities in the future. This assesses the magnitude of future risks and opportunities for two time periods, associated with the mid-century (2050s) and late-century (2080s), and for two scenarios, broadly consistent with 2°C and 4°C warming by the end of the century (globally, relative to pre-industrial – see Chapter 1: Slingo, 2021). It also considers ranges of uncertainty, where relevant information is available. The analysis considers the changes from extreme events and variability, as well as average (slow-onset) change. The relative importance of climate change as compared with other drivers of risk (i.e. socio-economics) is reported where possible, as well as distributional effects and potential inequalities. At the end of this task, the magnitude of future climate risks or opportunities is assessed using the categories set out in Table 2.2, in the absence of planned adaptation (the ‘no additional adaptation’ scenario), for each of the four countries. It also assesses the quality of the evidence and level of agreement, i.e. confidence (see Tables 2.4 and 2.5). This task also considers the evidence on low-likelihood, high impact scenarios, which are reported but not used to assess the likely magnitude, as well as the potential linkages with Net Zero from the risk/opportunity.

**Step 1c. Lock-in and thresholds.** This task identifies the potential risks of lock-in, i.e. where decisions (or inaction) in the next five years or so could ‘lock-in’ exposure or vulnerability to future climate risks that are difficult or very costly to address later. The risk of lock-in is identified and reported in Step 1 and then used during the consideration of the benefits of further adaptation in Step 3. This task also considers possible thresholds associated with risks or opportunities, and if the exceedance of these might necessitate different adaptation interventions (for either the 2°C or 4°C warming pathways by end of century globally, and also across uncertainty ranges for each of these scenarios). The potential for lock-in and threshold risks is reported alongside the magnitude scoring table, and in the adaptation and the urgency analysis. It is noted that lock-in and thresholds can also be relevant for opportunities.

**Step 1d. Interacting and cross-cutting risks.** This task investigates cross-cutting risk linkages and interdependencies for each risk and opportunity. The analysis of interdependences is considered in

the magnitude scoring and has the potential to increase the score. For opportunities, the potential for interdependent and cross-cutting effects, as well as co-benefits or trade-offs, are also considered.

## 2.5.2 Step 2: Analysis of Government and non-Government adaptation action

This step assesses the influence of adaptation in reducing current and future climate change risks, or enhancing potential opportunities, and therefore if risks and opportunities are being managed. This second step includes the following tasks:

**Step 2a. Analysis of current adaptation policies.** This step assesses the potential benefits of current and announced adaptation policy in reducing risks or enhancing opportunities. It starts by identifying the policy landscape, identifying organisational responsibilities, and existing adaptation policy and plans from Government and other agencies. This is used to produce a current adaptation policy scenario. The analysis assesses the potential impact of existing adaptation (in place) in reducing total current risks or enhancing opportunities. It then assesses the potential impact of current and announced planned adaptation in reducing future risks or enhancing opportunities, for the same time periods as step 1b (medium-term and long-term) for different future scenarios (2°C and 4°C future warming by 2100 globally) taking account of uncertainty. This analysis is undertaken for each country as well as overall UK actions for non-devolved issues. This also assesses the quality of the evidence associated with adaptation (see Tables 2.4 and 2.5).

**Step 2b. Non-Governmental adaptation.** In cases where there are still medium or high magnitude risks in any of the likely climate/socioeconomic scenarios considered (not the low likelihood, high impact scenario), or further opportunities, the analysis considers the potential impact of other forms of adaptation. This includes spontaneous and reactive adaptation (e.g. in natural systems, from acclimatisation, or in markets) in response to the changing climate, but also planned adaptation by non-government actors, e.g. proactive, planned private adaptation. The aim is to establish whether risks will be managed in the absence of further government intervention. The analysis also considers if this adaptation is likely to be beneficial, defined through the lens of overall social welfare. For opportunities, the analysis considers whether non-governmental adaptation is likely to lead to benefits being fully realised without planned Government action, or whether additional action may be needed, including creating the enabling environment for this to happen.

**Step 2c. Analysis of Adaptation Gap and Barriers to adaptation.** At the end of this task, there is a re-analysis of the magnitude of future risks or opportunities, taking into account planned and non-governmental adaptation. This identifies if these risks/opportunities are being managed or if there is still an adaptation gap (an adaptation deficit, see section 2.7 for criteria). This analysis is undertaken for each of the four countries. Where an adaptation gap exists, the analysis considers the barriers or constraints to adaptation, i.e. what might be stopping government, private sector, households, etc. from adapting.

## 2.5.3 Step 3: Analysis of the need and urgency for additional adaptation

In the case where an adaptation shortfall is identified in Step 2 (i.e. the risk has a residual high, medium or unknown magnitude score in any of the likely climate/socioeconomic scenarios

considered), the final step considers the potential benefits of additional adaptation, over and above what is currently happening or planned. This includes the following tasks:

**Step 3a. Identify and assess possible additional adaptation action.** This identifies an additional adaptation scenario to consider further adaptation to reduce risks or enhance opportunities. It considers the type of adaptation that could be taken (aligned to Figure 2.3), whether individual areas or as a portfolio or pathway. The aim is to identify where further action would be beneficial in managing risks or opportunities, whether through direct Government intervention or by creating the enabling environment for others, but it does not identify or suggest specific adaptation policies. While the focus is on the additional action in the next adaptation reporting period, this task also considers what action might be needed now in the context of longer-term pathways. For opportunities, the task considers what additional planned adaptation might be beneficial to fully realise potential benefits from climate change.

**Step 3b. Assess the indicative costs and benefits of additional action.** This task assesses the economic rationale for, and the indicative costs and benefits of the identified further action (including wider co-benefits or trade-offs), primarily in qualitative terms. This information helps to identify the possible areas for action (aligned to Figure 2.3) and to provide some context on the possible benefits of further action as compared to costs. This task also checks if there are any synergies or trade-offs with mitigation.

**Step 3c. Analysis of overall urgency scores.** At the end of this step, an analysis is made of the overall urgency score of each risk or opportunity. This categorises risks and opportunities into one of four scores: 'more action needed'; 'further investigation'; 'sustain current action' or 'watching brief'. Alongside this ranking, the assessment describes what type of action might be beneficial to manage the risks or opportunities, particularly in the context of the next National Adaptation Programme and adaptation programmes of the DAs. The urgency scores are set out in each chapter and summarised in the Advice Report. This step also assesses the quality of the evidence for the urgency ranking (see Tables 2.4 and 2.5).

**3d. Learning and Evaluation.** The last step is to move beyond the five-year focus of the CCRA3 cycle and ask the question of where additional information or analysis would be useful to inform CCRA4 and subsequent adaptation programmes, i.e. with respect to risks and adaptation. Teams were also asked to explicitly consider if/where transformational adaptation might be needed.

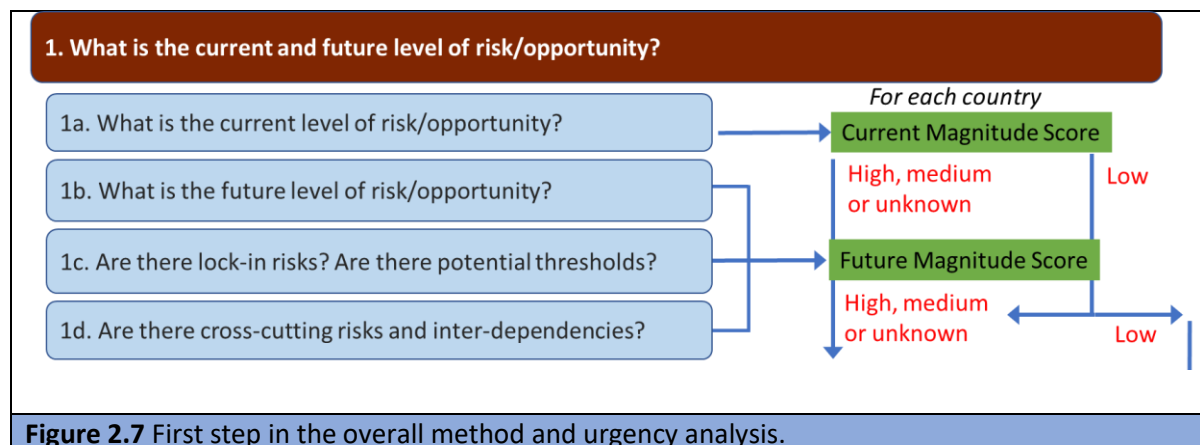
Finally, following the publication of the CCRA3 Evidence and Government Report and the next set of national adaptation programmes, it is recommended that a formal evaluation of CCRA3 should be undertaken prior to the CCRA4. This would need to be undertaken in 2023, after the publication of the CCRA3 Technical Report, Advice Report, Government Report and the National Adaptation Programme. As yet, resource has not been allocated to this task and will need to come from the UK Government.

## 2.6 Detailed Description of the Method

The detailed methodology for CCRA3 Technical Report is set out below by task and step.

## 2.6.1 Step 1. Assessment of Current and Future Risks and Opportunities

The first step in the overall method is the assessment of risks and opportunities (see Figure 2.7). This step starts with the analysis of current and potential risks and opportunities, and undertakes an initial scoring of their magnitude, then considers how these may change in the future.



**Figure 2.7** First step in the overall method and urgency analysis.

These steps are described in more detailed below.

### 2.6.1.1 Task 1a. Understand Present Day Risks and Opportunities

The purpose of the first task is to provide a summary of the current risks and opportunities from climate and non-climate stressors. An understanding of how hazard, exposure and vulnerability to the current climate (including climate change that has already taken place) allows for a better understanding of how risks and opportunities may change in the future. It also provides inputs to help assess the size of the current adaptation deficit.

The key terms for defining risks in CCRA3 (see Box 2.1) are based **on the IPCC definition of risk, and the components of hazard, exposure and vulnerability** (IPCC core concepts, IPCC, 2014a: IPCC, 2014b). This is worth being clear about as definitions of ‘risk’ – and methodological approaches - do vary across UK government (see Introduction Chapter: Betts and Brown, 2021). To assess current climate-related risks, CCRA3 authors were asked to assess the following:

- The current risks of climate on economic, social and environmental systems. This includes the consideration of year-to-year variability and extreme events, as well as from average climate.
- The key socio-economic factors that influence vulnerability, how these interact with climate and what is their relative importance or contribution. To support this task, an additional CCC research project was commissioned to update UK socio-economic data to use in the other research projects and across the report.
- Given the above, what the magnitude of the risks and opportunities is at present. This uses the magnitude table shown in Table 2.2. This scoring was undertaken separately for each UK country (England, Northern Ireland, Scotland and Wales), including the adjustment factors in Table 2.3.
- Assesses the quality of the evidence and level of agreement, i.e. confidence (see Tables 2.4 and 2.5)

A key focus for authors was to identify and document additional changes in the current risk or opportunity observed since CCRA1 or CCRA2. This included any weather-related thresholds, geographic ‘hotspots’ or types of event that pose a specific risk.

It is noted that the climate of the UK has already changed since pre-industrial times, and significant changes have occurred since the 1961-1990 period in both mean climate and extremes (Kendon et al., 2018), as outlined in Chapter 1 (Slingo, 2021). These changes become more important with each successive CCRA. This includes evidence of warming in annual mean temperature, the hottest and coldest days of the year, changes in annual precipitation, the most intense rainfall events, and the length of warm spells, dry spells and growing season length.

An additional element that was included in CCRA3 is the evidence that even in the present day, there is a higher probability of climate events that could happen but have not yet occurred in the observational records (Thompson et al., 2017 and Smith et al., 2019), as an example, temperatures exceeding 40°C. This has been considered using new methods that consider the likelihood of extreme and unprecedented weather events under the current climate, using a technique known as “UNSEEN” (UNprecedented Simulation of Extremes with ENsembles), as outlined in Chapter 1 (Slingo, 2021). Information on these events were compiled, and chapter authors were encouraged to consider the implications of these results, i.e. whether they affect their assessments of present-day climate impacts and risk. Additional information is given in Box 2.4 in the next section below.

For opportunities, the focus was also on understanding the current influence of climate on economic, social and environmental systems. However, the IPCC hazard-exposure-vulnerability framework does not work well for opportunities. Instead, the focus was on the magnitude of potential beneficial consequences (using the same categories of magnitude as for risks, but opposite in sign). This can involve the positive existing influence of the climate (i.e. as a baseline to allow comparison of rising future benefits under climate change) or the current negative impact of extremes to allow analysis of future decreases from climate change, such as for cold-related extremes.

At the end of this task, an analysis of the magnitude of current risks or opportunities was made (see section and Table 2.2 below). It is stressed that this magnitude score is undertaken for each individual country (England, Northern Ireland, Scotland and Wales), see also Table 2.3. The assessment also considers the confidence of the risks or opportunity, based on the level of agreement combined with the quality of the evidence used.

An interesting finding from the application of this approach is that adaptation is influencing current risks and opportunities. This creates new methodological challenges. In cases where the analysis of current risks (or opportunities) is based on observed information, these will reflect current levels of adaptation. However, any observed changes will also be influenced by other drivers, e.g. from changes in exposure or vulnerability, plus non-climate policy. This makes it extremely difficult to attribute the benefits of current adaptation in reducing current risks (without more detailed counterfactual analysis). Furthermore, to analyse the benefit of current adaptation, it is necessary to go through the tasks in Step 2 (identify who is responsible, what current adaptation policy is, and how effective it is). For these reasons, the analysis of the role of current and future adaptation was included in Step 2.

More information on the magnitude and confidence scoring, and supplementary activities on economic valuation and distributional effects and inequalities, is given below.

#### 2.6.1.1.1 Magnitude scoring

The final task in the first step of the method is to assign a magnitude score to each risk and opportunity. This is undertaken for both current and future time periods.

Most risk assessments seek to assign an overall magnitude using a combination of likelihood and impact. For example, the UK National Security Risk Assessment and the National Risk Register (NRR) (HMG, 2020) - which consider risks (national-scale emergencies) assuming a reasonable worst case - assesses the combination of likelihood (within the next five years) and the impact severity to provide an overall ranking of risks. CCRA3, however, is working with a broader defined set of risks (see Box 2.1 key terms), which include long-term trends as well as probabilistic events, over a much longer-time frame.

A magnitude scoring approach was developed in CCRA2 to capture potential impact of trends and probabilistic events, and this has been applied again in CCRA3. The impact levels were set based on a review of the NRA.

This magnitude table has been updated in CCRA3. This extended the table with a larger number of categories, particularly to capture potential magnitude for the natural environment and natural capital, see Box 2.3 below (as these are not captured in many existing risk frameworks, such as the NRR). The new table added additional categories (rows), but also undertook a re-analysis to improve the cross comparability between magnitude rankings (columns) and between categories (rows) using a valuation and benchmarking exercise. This resulted in some changes in the magnitude descriptions as compared to CCRA2. The updated categories and magnitude scores used in CCRA3 are shown in Table 2.2.

Where possible, the evidence was matched to the relevant category and magnitude in the table. However, in some cases such evidence does not exist, and the analysis allows for expert judgement to be used. To make this process robust, this was based on the consensus (through consultation and discussion) of Technical Report authors, the CCC, and the CCRA peer reviewers.

A further change in CCRA3 has been to provide different magnitude tables for each UK country (England, Northern Ireland, Scotland and Wales). This aims to provide an equivalent relative magnitude score of risks or opportunities for each country, i.e. to provide consistent relative scores of what is important for each DA. This approach was used because the use of a single scoring table led to important omissions (of magnitude) for the three DAs. This does, however, mean that risks or opportunities in each country do not have the same absolute risk or opportunity level. For England and the UK, Table 2.2 was used without adjustment. For other DAs, the values were adjusted using the information in Table 2.3. Note that scoring below the level of the DAs (at a more disaggregated level or for hotspots) has not been undertaken.

The evidence from the review was used with Table 2.2 and 2.3 to assign a low, medium or high magnitude to each risk or opportunity - there is also an option of an 'unknown' score in case there is insufficient evidence. Opportunities were assessed using the same magnitude level, but with opposite sign.

It is stressed that these categories are not mutually exclusive, but are a set of options from which chapter authors could choose based on the evidence available. They were asked to choose from the categories to score a risk in the fullest way possible with the evidence available. It is acknowledged that in some cases, the available evidence will represent an underestimate of the total scale of risk or opportunity, thus a logarithmic scale is used to reduce the sensitivity to gaps in the evidence.

The other main development in CCRA was the consideration of future risks across different future time periods and scenarios, in line with the customer request. The resulting scoring table is presented in section 2.6.2.

**Box 2.3 Natural Environment and Natural Capital.**

In considering the size of risks or opportunities in the natural environment, different types of quantification are possible depending on what is being measured. This could be the size of a natural capital asset (see below), the size of an area containing different assets, the change in the quality or quantity of a natural asset, the services it provides to people, or the value of those services. CCRA2 only provided magnitude categories for the area or size of habitats and species affected, but when looking at the definition of natural capital, it is clear that these measures do not capture the total risk. The additional categories in Table 2.2 are intended to allow for a fuller analysis depending on the evidence available. While the terms natural environment and natural capital are both included here to ensure comparability between this and past CCRA2s, going forward (including in CCRA4), it would be useful for these terms to be consolidated.

Natural capital is defined by NCC (2017) as follows: Natural capital are the elements of nature that directly or indirectly produce value to people, including ecosystems, species, freshwater, land, minerals, the air and oceans, as well as natural processes and functions. Natural capital is a broad term that includes many different components of the living and non-living natural environment, as well as the processes and functions that link these components and sustain life. Natural capital assets include all biotic and abiotic assets (e.g. species, ecological communities, soils, freshwaters, land, atmosphere, minerals, sub-soil assets and oceans) and include both designated and undesignated habitats and species. The magnitude of a risk on a natural capital asset can be measured using any of the quantitative or qualitative indicators in Table 2.2, and not just those described using the term 'natural capital'.



**Table 2.2** CCRA magnitude categories for UK and England.

	<b>High Magnitude</b>	<b>Medium Magnitude</b>	<b>Low Magnitude</b>
Quantitative evidence	<i>Major annual damage and disruption or foregone opportunities:<sup>1</sup></i>	<i>Moderate annual damage and disruption or foregone opportunities:</i>	<i>Minor annual damage and disruption or foregone opportunities:</i>
	-£hundreds of millions damage (economic) or foregone opportunities, and/or	-£tens of millions damage (economic) or foregone opportunities, and/or	-Less than £10 million damage (economic) or foregone opportunities, and/or
	-Hundreds of deaths <sup>2</sup> , thousands of major health impacts, hundreds of thousands of people affected / minor health impacts, and/or	-Tens of deaths, hundreds of major health impacts, tens of thousands of people affected / minor health impacts. and/or	-A few deaths, tens of major health impacts, thousands of people affected / minor health impacts, and/or
	-Tens of thousands of hectares land lost or severely damaged <sup>3</sup> , and/or thousands of km of river water/km <sup>2</sup> of water bodies affected, and/or	-Thousands of hectares of land lost or severely damaged, and/or hundreds of km of river water/km <sup>2</sup> of water bodies affected, and/or	-Hundreds of hectares of land lost or severely damaged, and/or tens of km of river water/km <sup>2</sup> of water bodies affected, and/or
	-Major impact (~10% or more at national level) to valued habitat or landscape types (e.g. BAP habitats, SSSIs), and/or	-Intermediate impact (~5% at national level) to valued habitat or landscape types (e.g. BAP habitats, SSSIs), and/or	-Minor impact (~1% at national level) to valued habitat or landscape types (e.g. BAP habitats, SSSIs), and/or
	-Major impacts on or loss of species groups, and/or	-Intermediate impacts on or loss of species groups, and/or	-Minor impacts on or loss of species groups, and/or
	-Major impact (10% or more at national level) to an individual natural capital asset and associated goods and services <sup>4</sup> , and/or	- Intermediate impact (1 to 10% at national level) to an individual natural capital asset and associated goods and services, and/or	- Minor impact (~1% or less at national level) to an individual natural capital asset and associated goods and services, and/or
	-Major loss or irreversible damage to single nationally iconic heritage asset (e.g. Stonehenge, Giants' Causeway)	-Medium loss or irreversible damage of nationally iconic heritage asset (e.g. Stonehenge, Giant's Causeway)	-Low loss or irreversible damage to nationally iconic heritage asset (e.g. Stonehenge, Giants' Causeway)
Qualitative evidence	Expert judgement of chapter authors, confirmed with agreement across authors, CCC and peer reviewers suggest there is a possibility of impacts of the magnitude suggested above.		

<sup>1</sup>This could be an annual average or expected annual damages. Where evidence is only related to a single event, authors should make a judgement on the magnitude and state this in their assumptions.

<sup>2</sup>The implied value of number of deaths is broadly in line with the value of prevented fatalities used by Government in the appraisal of policies (see DfT, 2019). It should be noted that this applies to an 'average' prevented fatality, i.e. someone of average age and who is otherwise healthy. The number of major injuries / major health outcomes, and minor injuries / minor health outcomes / people affected, are also in line with values used in appraisal.

<sup>3</sup>These values are based on the average value for an agricultural hectare of land in England that is estimated to be £22k ([https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/710539/Land\\_Values\\_2017.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/710539/Land_Values_2017.pdf)) It is noted that the average value for residential, commercial and industrial land is much higher, and thus if urban land areas are affected, these scoring categories might be adjusted, i.e. so that a lower number of hectares would be equivalent to a low, medium or high ranking.

<sup>4</sup>The areas of natural capital assets are based on the definitions and reported values in the ONS Natural Capital Accounts and expert analysis of equivalence, <https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapitalaccounts/2019>.

**Table 2.3** Adjustment factors for scoring magnitude for devolved administrations.

	England	Northern Ireland	Scotland	Wales
Economics	As table above	Metrics in table above adjusted for gross value added <sup>1</sup> , thus to give relative importance, values in table are reduced by 1 order of magnitude, and applied equally to Northern Ireland/Scotland/Wales. <ul style="list-style-type: none"> <li>• Tens of millions damage or foregone opportunities,</li> <li>• £ millions damage or foregone opportunities</li> <li>• Less than £1 million damage or foregone opportunities.</li> </ul>		
Health	As table above	Metrics in table above adjusted for population <sup>2</sup> , factoring down levels in table by 1 order of magnitude, and applied equally to all DAs. <ul style="list-style-type: none"> <li>• Tens of deaths, hundreds of major health impacts, tens of thousands of people affected / minor health impacts, and/or</li> <li>• A few deaths, tens of major health impacts, thousands of people affected / minor health impacts, and/or</li> <li>• No deaths, a few major health impacts, hundreds of people affected / minor health impacts, and/or</li> </ul>		
Land	As table above	Metrics in table above adjusted for land <sup>3</sup> , factoring down levels in table by 1 order of magnitude. <ul style="list-style-type: none"> <li>• Thousands of hectares land lost or severely damaged,</li> <li>• Hundreds of hectares of land lost or severely damaged,</li> </ul> Tens of hectares of land lost or severely damaged.	Given high land area of Scotland (approx. one third of UK) values in table above are used.	Metrics in table above adjusted for land <sup>3</sup> , factoring down levels in table by 1 order of magnitude. <ul style="list-style-type: none"> <li>• Thousands of hectares land lost or severely damaged,</li> <li>• Hundreds of hectares of land lost or severely damaged,</li> </ul> Tens of hectares of land lost or severely damaged.
Habitat / Natural capital	As table above	As table above.		

<sup>1</sup> Economics. Gross Value Added (GVA) is taken from Office for National Statistics  
<https://www.ons.gov.uk/economy/grossvalueaddedgva/bulletins/regionalgrossvalueaddedbalanceduk/1998to2017>

	GVA (2017 £M)	%
England	1,562,707	86.7%
Northern Ireland	39,613	2.2%
Scotland	138,231	7.7%
Wales	62,190	3.4%
UK	1,802,741	

<sup>2</sup> Population is taken from the Office for National Statistics – National population projections  
<https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/nationalpopulationprojections/2018based#table-1408dbb6>

2018	Million	%
England	56.0	84%
Northern Ireland	1.9	2.9%
Scotland	5.4	8.1%
Wales	3.1	4.7%
UK	66.4	

<sup>3</sup> Land area is taken from the Office for National Statistics using latest land cover accounts.  
<https://www.ons.gov.uk/economy/environmentalaccounts/articles/uknaturalcapitalandcoverintheuk/2015-03-17>

	Thousand Hectares	
England	13,043	53.4%
Northern Ireland	1,415	5.8%
Scotland	7,881	32.3%
Wales	2,078	8.5%
UK	24,417	

## 2.6.1.1.2. Quality of Evidence and Level of Agreement (Confidence)

In the IPCC AR5 synthesis process (Mach et al., 2017), assessment findings are evaluated against (a) evidence and agreement, (b) confidence, and (c) likelihood. For CCRA3, a formal method was used to assess the quality of the evidence used in terms of evidence and agreement, and thus confidence.

In terms of the quality of evidence, there is a requirement that evidence be from:

- Published papers in academic and professional journals;
- Papers *in press* in academic and professional journals (*copies of these should be made available to the reviewers, and have been published by the time the CCRA3 Technical Report is published*);
- Published (or publicly available, including at cost) reports from research institutions, Government agencies, Government committee reports, papers and minutes (and responses to consultations), third-sector organisations or private sector companies (including contract research reports), as well as grey literature that has been through a review process and is published.

These sources of evidence were recommended *not* to be used:

- Papers that have been ‘submitted’ or are ‘in preparation’ at the time of the publication of the CCRA3 Technical Report:
- Reports that are not publicly available, even at cost.

To assess the confidence a simplified version of the IPCC AR5 approach is used, looking at the combination of the quality of evidence as set out above (from high to low), along with the level of agreement between studies and experts (high to low). These are combined to give the overall confidence ranking. Note that the confidence is a measure of the strength of evidence and

agreement, and is different to the likelihood that the risk or opportunity will occur. Table 2.4 provides the criteria used to assign a confidence score to each risk and opportunity in Step 1. There is also a similar quality of evidence and agreement included for assessing the effect of adaptation in Step 2 and if additional action would be beneficial in Step 3. Additional supplementary information for assessing the quality of evidence is included in Table 2.5.

**Table 2.3** Quality of Evidence and Level of Agreement (Confidence) – Criteria.

	<b>High</b>	<b>Medium</b>	<b>Low</b>
<b>Step 1: Assessment of current and future risk</b>	Multiple sources of independent evidence based on reliable analysis and methods, with widespread agreement between studies and experts.	Several sources of high-quality independent evidence, with some degree of agreement between studies, and/or widespread agreement between experts.	Varying amounts and/or quality of evidence and/or little agreement between experts, or assessment is made using only expert judgement.
<b>Step 2: Assessment of the effect of planned and non- Governmental adaptation</b>	High quality evidence of the effects of future adaptation in managing the risk and high agreement between experts.	Some evidence on the effects of future adaptation in managing the risk and/or high agreement between experts.	Little/no/contrasting evidence of the effects of future adaptation in managing the risk and little agreement between experts, or assessment is made using only expert judgement.
<b>Step 3: Assessment if additional action would be beneficial</b>	High quality evidence of benefits of future adaptation on risk and high agreement between experts.	Some evidence on benefits of future adaptation and/or high agreement between experts.	Little evidence of the benefits of future adaptation and little agreement between experts, or assessment is made using only expert judgement.

**Table 2.4** Supplementary information for assessing Quality of Evidence.

High quality evidence	Some evidence	Little evidence
<ul style="list-style-type: none"> <li>Multiple sources of evidence that contain similar results</li> <li>Evidence of validation using different datasets</li> <li>Based on robust techniques</li> <li>Data used is of a high quality</li> <li>Evidence has been peer reviewed</li> <li>Remains relevant</li> <li>Use of relevant indigenous and local knowledge</li> </ul>	<ul style="list-style-type: none"> <li>Some elements of “high quality evidence” and “little evidence”</li> </ul>	<ul style="list-style-type: none"> <li>No, or very few, sources of evidence</li> <li>Based on only one dataset</li> <li>Based on weak methodologies (e.g. anecdotal evidence)</li> <li>Poor quality data</li> <li>Evidence has not been peer reviewed</li> <li>No longer relevant</li> <li>No use of relevant indigenous and local knowledge</li> </ul>

## 2.6.2 Task 1b Assess Future Risks and Opportunities

The second task undertakes an analysis of the future risks and opportunities of climate change, repeating the steps above but for future time periods. This step also considers risks in terms of hazard, vulnerability and exposure. However, it involves the additional challenge of different future climate projections, uncertainty and future socio-economic change. The task applied the IPCC Core Concepts to assess future risks, while noting that the components of hazard, exposure and vulnerability are dynamic and change over time. For opportunities, the focus was on the magnitude of potential consequences. The CCRA authors were asked to consider the following issues:

- How relevant climatic factors, and risks or opportunities, may change in the future, including an assessment of the uncertainties.
- How socio-economic factors could influence the risk/opportunity in the future and their influence on magnitude.
- To record evidence for the risks and opportunities in the mid-century (2050s, i.e. 2041-2060) and late-century (2080s, 2070 – 2099), including the uncertainties associated with the climate evidence. This also included the differences in future risks or opportunities for pathways to warming of 2°C and 4°C by the end of the century, globally, relative to pre-industrial, where available, including quantification of uncertainty. Authors were asked to record the reference period used (noting UKCP18 is now using 1981-2000). They were also asked to document the assumptions on socio-economic scenarios and to document the relative importance of climate versus socio-economic (if available). When evidence was based on global warming levels, the teams were asked to document the Global Warming Level (GWL) and time period (e.g. 2°C GWL global mean temperature (GMT), relative to preindustrial, exceeded in time period centred on 2070).
- To capture and report on any low-likelihood high-impact extremes or scenarios. This included High++ runs, tail-end risks, higher warming scenarios (e.g. > 4°C by 2100) and earth system tipping points.
- To identify any potential risks of lock-in (see section 2.3), or loss of opportunities, particularly where decisions might be taken in the next reporting period (the next 5 years). They were also

asked to document important thresholds (whether biophysical thresholds, engineering, performance or policy thresholds, see section 2.3) and consider if the exceedance of these varied over scenarios or across projections (including uncertainty). Authors were also asked to assess the potential synergies and trade-offs with Net Zero, as part of a separate set of questions.

- To assess the magnitude of the risks and opportunities in the future and how important climate change is in the realisation of a risk.

At the end of this task, the same magnitude scoring approach as for Task 1a (Tables 2.2 and 2.3) were used to score future risks and opportunities. This was undertaken separately for each UK country (England, Northern Ireland, Scotland and Wales).

For the first round of magnitude scoring (in early 2020), authors were asked to assess future magnitude (High, Medium, Low or Unknown) as one single score, which reflected the highest score across different time periods, scenarios or pathways, and across the uncertainty range. Note that this approach is inherently precautionary, and followed the approach used in CCRA2.

For the second round of scoring (summer to autumn 2020), authors were asked to assess magnitude in line with the request from Government. This included information on potential risks and opportunities under different time periods (mid-century and late century) and different future pathways, defined broadly in terms for 2°C and 4°C pathways by the end of the century (globally, relative to pre-industrial levels)<sup>2</sup> as well as for each DA. Authors were asked to provide the highest score across the uncertainty range in each cell. This is shown in Table 2.6 below.

An assessment of the quality of the evidence and level of agreement, i.e. confidence, was also undertaken and included in brackets after the magnitude score (Tables 2.4 and 2.5).

A number of additional aspects to consider were also requested. Authors were asked to consider the implication of different rates of climate change between the two scenarios, not just the absolute change, as this is extremely important in determining adaptation potential. They were also asked to consider the distributional effects and potential inequalities associated with risks and opportunities (see section in 2.6.1.).

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<sup>2</sup> This did not include a scenario that limits warming to 1.5°C, i.e. to consider an additional scenario that was closer to the Paris Agreement text of pursuing efforts to limit warming to 1.5°C relative to pre-industrial. This 1.5°C scenario has received more attention following the recent IPCC Special Report on Global Warming of 1.5 °C (IPCC, 2018). CCRA3 has not considered such a 1.5°C scenario, see Chapter 1. This is primarily due to the lack of information to inform a risk assessment at this level. However, it is noted that global emissions are still rising and current pledges for reducing emissions, as set out in the Nationally Determined Contributions, indicate warming of above 3°C (UNEP, 2019; UNEP, 2020). This analysis has also identified limiting warming to 1.5°C would require global emissions to fall by 7.6% per year from 2020 to 2030. The progress towards such reductions will become clearer during the Global Stocktake (in 2020, now delayed to 2021), which will review the implementation of the Paris Agreement and assess collective progress and updates towards achieving the Paris Agreement and its long-term goals.

**Table 2.5** Magnitude Scoring summary table in CCRA3. Each cell was assigned a score of low (L), medium (M), high (H) or unknown (U).

	Present Day	2050s		2080s	
Country		On a pathway to stabilising global warming at 2°C by 2100*	On a pathway to 4°C global warming at end of century#	On a pathway to stabilising global warming at 2°C by 2100*	On a pathway to 4°C global warming at end of century#
England	L/M/H/U	L/M/H/U	L/M/H/U	L/M/H/U	L/M/H/U
Northern Ireland	L/M/H/U	L/M/H/U	L/M/H/U.	L/M/H/U	L/M/H/U
Scotland	L/M/H/U	L/M/H/U	L/M/H/U	L/M/H/U	L/M/H/U
Wales	L/M/H/U	L/M/H/U.	L/M/H/U.	L/M/H/U	L/M/H/U

\*This scenario is defined as the global mean temperature rise stabilising at 2°C ± 0.5°C by 2100. This includes pathways that align to the Paris Agreement and the goal of limiting global mean temperature rise to well below 2°C above pre-industrial levels, and also pathways that slightly exceed this global warming level, including “overshoot” pathways.

# This scenario is defined around outcomes that lead to a 4°C global mean temperature rise above pre-industrial levels at the end of the 21<sup>st</sup> century (2080 to 2100). This is considered an upper bound of global warming rates that could occur with current policies, considering various combinations of emissions scenarios and climate system feedbacks (see Introduction chapter: Betts and Brown, 2021).

A supplementary analysis was undertaken to investigate the indicative monetary impacts of future risks and opportunities (see section in 2.6.1.). Alongside this magnitude score, authors were also asked to consider possible low likelihood, high impact extremes and scenarios (including high warming outcomes that reach 4°C before 2070, High++, tail-end risks and earth system tipping points). However, the evidence (on low likelihood, high impact) was not used in the magnitude scoring.

It is stressed that the primary aim of this task was to identify the magnitude of future risk and opportunities in the absence of planned adaptation - the analysis of adaptation in managing these future risks is undertaken in step 2. However, for studies that undertake modelling of risks and adaptation, including the CCRA3 research projects, it was necessary to define no adaptation baselines. To address this, CCRA3 defined a Step 1 future ‘no additional adaptation’ scenario. This included ‘common sense’ assumptions on what might happen in the absence of planned policy. This is the same approach that was used in CCRA2.

One lesson from the application of the method for opportunities was that in most cases, these are complicated by the presence of potential risks alongside benefits, e.g. where there were potential benefits identified from a warmer average climate, there were often still potential impacts from changing variability or extremes, or other factors such as water availability limiting the ability for enhanced crop growth in warmer temperatures. In such cases, authors were asked to document both aspects.

More information on key elements of this task – on climate projections, socio-economic scenarios, the Net Zero analysis, and tail-end risks - are given below.

### 2.6.2.1 Climate change projections, including uncertainty

The starting point for the assessment of future risks and opportunities are the climate projections, set out in Chapter 1 (Slingo, 2021). There are different ways to use these projections in climate risk assessments, and to ensure consistency of reporting for different risks and opportunities. However, these consistency issues are a particular challenge for a synthesis exercise, such as CCRA3, because it must draw on various evidence that uses different projections and approaches.

In previous CCRAs, and in most impact studies, analysis or evidence is assessed for future scenarios and time periods. In CCRA1, a consistent set of projections and time slices from UKCP09 were used and applied to every risk or opportunity. This used the UKCP09 time slices<sup>3</sup> for the 2020s (represented by the mean climate for 2010-2039), 2050s (2040-2069), and 2080s (2070-2099) relative to a baseline period of 1961-1990 and considered the UKCP09 low, medium and high UKCP09 projections, as well as sampling the probabilistic projections<sup>4,5</sup>. CCRA2 was a synthesis exercise, but asked contributors to report evidence for the 2050s, and 2080s, including a discussion on the uncertainties associated with the climate evidence used. The authors considered climate projections on a country-by-country basis, for the subsequent risk and opportunity assessment. In CCRA2, this was based on country averages, but with commentary around how this varied spatially.

As set out in Chapter 1 (Slingo, 2021), and earlier in this Chapter, the UK has now published a new set of climate projections, the UK Climate Projections 2018 (UKCP18). The UKCP18 overview report (Lowe et al., 2018) reported changes for two future time periods (of twenty years) – the 2050s (2041-2060) and 2080s (2080 – 2099), relative to a baseline period of 1981-2000, though the UKCP18 projections also provide a time series that runs continually from pre-present through to 2100. The UKCP18 products allow analysis of projections with the RCP2.6, RCP4.5, RCP6.0 and RCP8.5 emissions scenarios, and also some potential to extract information specifically for 2°C and 4°C global warming levels relative to pre-industrial (Gohar et al., 2018). The latter allows for an alternative approach to reporting results, using global warming levels (GWL), rather than for time periods for emission / forcing scenarios. However, it is stressed that for adaptation, the time period when risks or opportunities occur and the rate of adaptation needed are important, and therefore approaches that use GWL need to document time, as has been done here. It is also possible to extract subsets of the projections that follow pathways that reach these global warming at specific times such as at the end of the 21<sup>st</sup> Century, and this has been done in some of the CCRA3 supporting research (Sayers et al., 2021) and in other literature drawn on for the CCRA3 assessment (e.g. Arnell et al., 2021)

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<sup>3</sup> Note that projections are generally presented as averages for twenty-year or thirty-year time periods, not as decadal or yearly averages, because decadal periods are still subject to significant natural variability and may not give a good indication of the long-term climate.

<sup>4</sup> CCRA1 sampled across the p10, p50 and p90 for the UKCP09 low medium and high projection and focused on nine combinations (results) as follows: 2020s: p10 Medium, p50 Medium, p90 Medium; 2050s: p10 Low, p50 Low, p50 Medium, p50 High, p90 High; and 2080s: p10 Low, p50 Low, p50 Medium, p50 High, p90 High.

<sup>5</sup> It is interesting to note that the CCRA3 Independent Assessment and the next national adaptation programme period (2023-2027) is at the mid-point of the UKCP09 2020s time period.



In gathering existing information on the evidence in CCRA3, authors were asked to understand and assess how climate and socio-economic change may alter climate-related risks and opportunities for the mid-century (the 2050s, often represented by the mean climate for 2040 -2060) and late-century (2080s, or 2070 – 2100), for 2°C and 4°C warming pathways by the end of the century (globally, relative to pre-industrial levels), where possible. Authors were asked to be explicit about the reference (baseline) periods used for evidence.

As highlighted earlier, much of the literature on future UK climate risks assessed in CCRA3 is based on UKCP09. In practical terms, this raised an issue on how to use information from UKCP09 in CCRA3, given the different baseline and future periods<sup>6</sup>, as well as the updated information from UKCP18. To address this, the UK Met Office produced new information for authors, based on the key metrics of relevance for the identified risks and opportunities (see Chapter 1: Slingo, 2021). A summary is provided in Box 2.4.

In collecting this information, and assessing adaptation, it is important to consider uncertainty. This involves two issues. The first is that there are alternative future emission pathways, which is addressed by using several sets of projections sampling the emissions scenarios associated with the Representative Concentration Pathways, RCPs, as in UKCP18. The second issue is that different climate models do not all give the same results for UK climate for a given emissions scenario or even at the same global warming level. This can be considered by using different models in an ensemble, or as in UKCP18, with the derivation of a conditional probability range, with outputs of (for example) 10<sup>th</sup>, 50<sup>th</sup> and 90<sup>th</sup> percentiles. It is essential to recognise this uncertainty, not to ignore it.

#### Box 2.4. Supporting Climate Analysis for CCRA3.

**UKCP09 to UKCP18.** As noted in Chapter 1 (Slingo, 2021), some of climate risk-related quantities in UKCP18 are quite different to those in previous projections, while others are similar. Analysis by the UK Met Office for CCRA3 assessed key climate metrics (of relevance to the CCRA3 risks and opportunities) and provided information on when these differences were extensive enough to affect the advice previously provided by the CCRA around estimates of magnitude drawn from UKCP09, and also to take account of similarities when assessing confidence. To do this, the analysis in CCRA3 has used the following procedure for each Risk, (illustrated earlier in Figure 2.1).

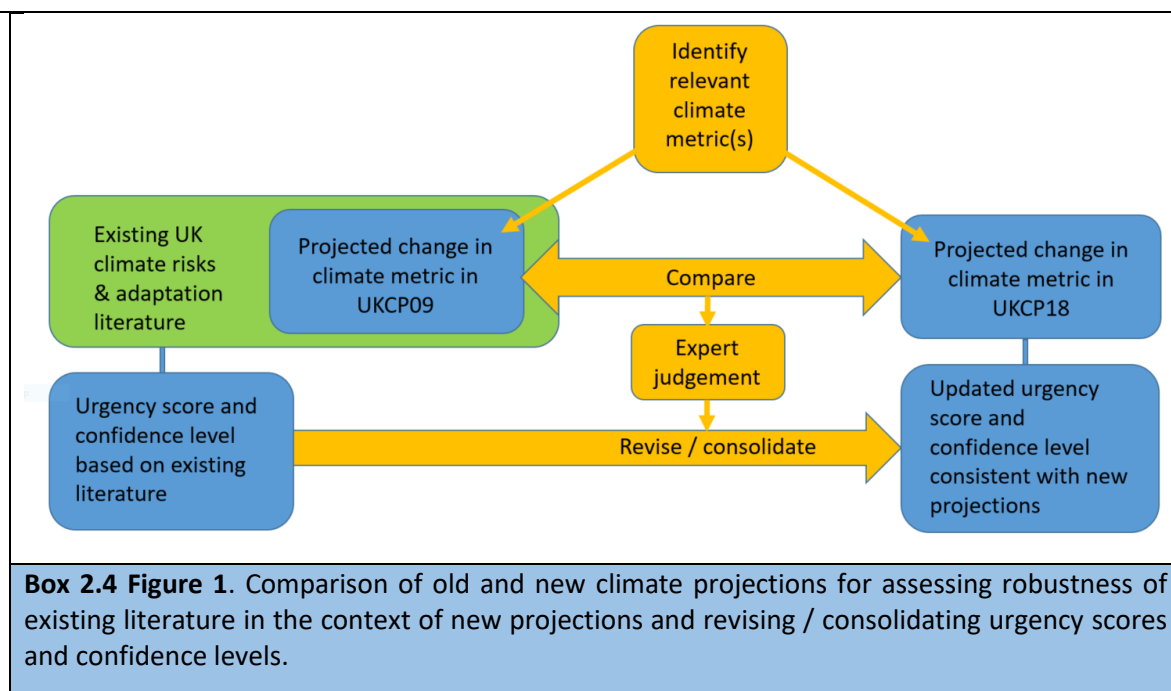
- Produce an initial magnitude score based on the existing UKCP09-based literature where relevant.
- Identify the key climate variables or metrics used to quantify the hazard component of the risk or opportunity in the existing UKCP09-based literature.
- Compare the projected changes in these variables and metrics from UKCP09 with the equivalent changes in UKCP18.
- Using expert judgement, assess whether the differences between the changes projected by UKCP18 and UKCP09 are substantial enough to justify a different magnitude score.
- If a different magnitude Score is justified by the UKCP18 projections, critically examine the underlying reasons for the difference in the projected climate variable / metric and form a

<sup>6</sup> Earlier impact studies, such as those based on UKCP09, use an earlier reference period (usually 1961-1990), but this is now out of date with respect to the current time (i.e. the year 2020). It is stressed that the magnitude does vary depending on whether risks compared with 1961-1990, 1981-2000 or the current.

judgement on which is the most robust. Reflect this change by use of an appropriate confidence statement. If a different magnitude Score is not justified, again critically examine the reasons for the similarity in the projected climate variable / metric, and assign an appropriate confidence level.

- Ascertain if the change in magnitude warrants a change in the urgency score.

The UKCP09-UKCP18 comparison used the UKCP09 regional climate model (RCM ensemble) and was performed most systematically with the UKCP18 12km projections, but the 2.2km projections were also considered. Furthermore, the UKCP18 60km global simulations were also used to provide further context. The results were examined to assess whether the changes in key metrics – and subsequent risks and opportunities where relevant - were substantial enough to justify a different magnitude and urgency score.



**Volatility, extremes and UNSEEN.** The climate of the future can be viewed as a long-term climate trend with natural variability superimposed on to it and providing volatility, which will be experienced as future weather. UKCP18 focuses more than UKCP09 on capturing climate volatility, with the conditional probability range including natural variability down to the monthly scale and the ensembles of realisations from global and regional climate models providing a tool to examine sub-monthly volatility (Lowe et al., 2018). Additionally, other tools are now available in the climate literature that focus on present day volatility and the possibility of seeing unprecedented events not captured in the relatively short observational record. These include the UNSEEN approach (Thompson et al., 2017), which uses many historical simulations to provide additional realisations of the events that might occur in the current climate. When assessing climate impacts, it is important to go beyond the long-term mean changes and to take account of volatility and extreme events, including unprecedented events. This can significantly widen the distribution of potential climate outcomes as Lowe et al. (2018) describe when showing probability distributions based on annual averages and multi-decade averages. From an impacts perspective it is useful for chapter authors to consider the time over which a threshold might be exceeded, relating this to natural climate variability where possible. There is also the potential to consider event-based

extremes, including the analysis of preparedness, based on previous analogues, e.g. as used in the National Flood Resilience Review for Storm Desmond.

As discussed in Chapter 1 (Slingo, 2021), the projected temperature and precipitation changes are broadly similar until the 2040s across all the scenarios (i.e. with similar results for RCP2.6, RCP4.5 and RCP6.0 and to a slightly lesser extent in results for RCP8.5). There is also only a small difference between the climate outcomes of these emissions scenarios even at mid-century (the 2050s). However, there is a much larger difference in the results between or within models at this time (in the 2050s). This means that the main uncertainty at mid-century is due to differences between (and within) the climate models - or to put another way – projections for the mid-century are broadly similar irrespective of the emissions scenario being assumed. This is illustrated by, for example, the 10<sup>th</sup> to 90<sup>th</sup> percentile range from UKCP09, or the 5<sup>th</sup> to 95<sup>th</sup> percentile range from UKCP18. As shown in Chapter 1 (Slingo, 2021), this leads to a considerable range, and for some parameters (e.g. summer rainfall), it can even lead to a change in the sign, from an increase to a decrease in the projected change.

As CCRA3 has the primary goal of informing adaptation, it is just as important to sample model uncertainty as it is to sample emission pathway uncertainty, especially for the medium term (2050s), which is of most interest for informing early adaptation. Authors were asked to consider the conditional probability range, specifically the 10<sup>th</sup> to 90<sup>th</sup> percentiles in the UKCP09 or UKCP18 projections, but in practice it was extremely difficult to do this in a synthesis exercise such as CCRA3, though authors considered ranges of uncertainty where relevant information was available.

Towards the late-century (2100) the RCPs diverge significantly, as shown in Chapter 1. At the end of the century (2100) there are large differences between the central estimate pathways, although the very large differences across the percentile ranges mean that there is still a large overlap between the outcomes for the different RCPs, especially for precipitation changes at the UK scale (see Chapter 1).

A further issue is that different sets of climate projections use different emissions scenarios and different approaches for implementing these in climate models. For example, UKCP09 used the SRES emissions scenarios. The 5<sup>th</sup> Coupled Model Intercomparison Project (CMIP5) projections for IPCC AR5 used the Representative Concentration Pathways (RCPs) which were defined in terms of concentrations of CO<sub>2</sub> and the resulting radiative forcing, as opposed to emissions. UKCP18 used yet another approach – it used emissions scenarios that were designed to align with the RCP concentration pathways based on a specific assumption of the strength of climate-carbon cycle feedbacks, but then made its own calculations of the future concentrations accounting for uncertainties in the feedbacks. The evidence base available to CCRA3 included studies using all these different approaches.

To account for these uncertainties in both future emissions and the responses of the climate to these emissions, whilst avoiding reliance on specific methods and hence excluding important bodies of evidence in the literature, CCRA3 characterises future climate change in terms of two pathways. These are defined as broad pathways to approximately 2°C and 4°C global warming at the end of the 21<sup>st</sup> Century (Box 2.5). This allows the use of more evidence, as it can include scenarios or emissions (or radiative forcing) and time slices, as well as warming levels. The assessment considers risks and

opportunities on the basis of studies using climate projections consistent with these 2°C and 4°C pathways. The uncertainty range across each pathway is considered as far as possible, and the Step 1 assessment uses the highest resulting magnitude score for across each scenario (across the uncertainty range) and time period. The analysis of whether the risks and opportunities are being managed across both the 2°C and 4°C pathways is considered in the subsequent Step 2.

**Box 2.5. Characterising future climate change: pathways to 2°C and 4°C global warming at the end of the 21<sup>st</sup> Century.**

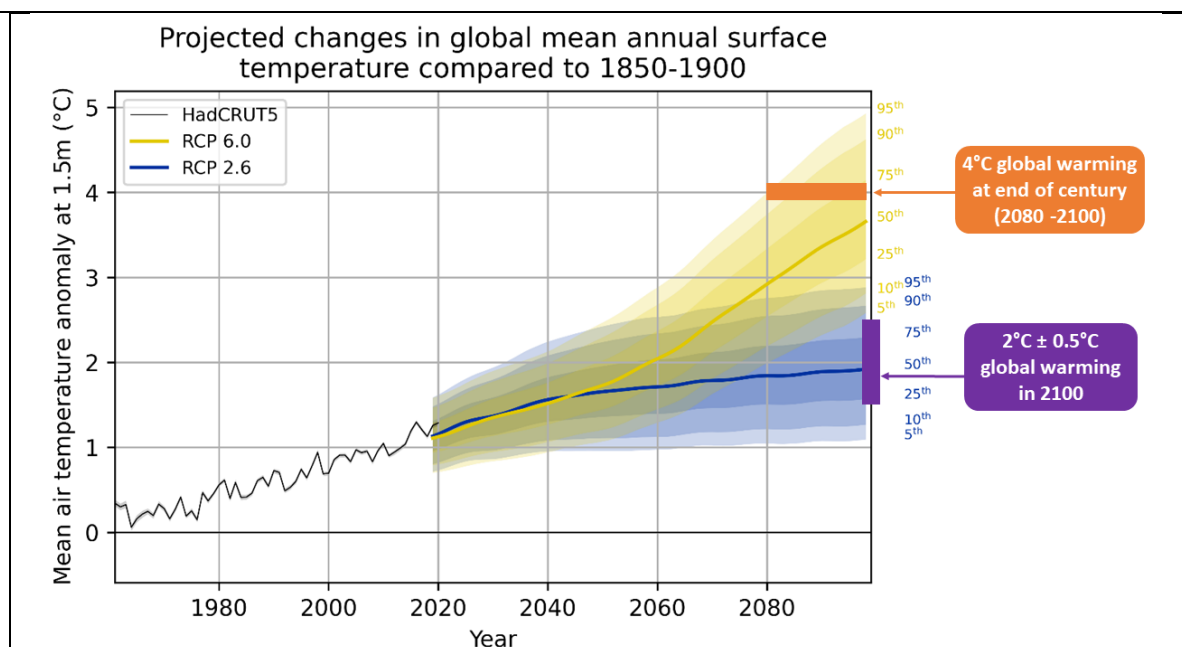
In the mitigation domain, the characterisation of 2°C and 4°C warming pathways is a useful proxy for considering the costs of inaction, and the possible benefits of global emissions reductions e.g. in line with the Paris Agreement goals. However, the aim of the CCRA3 is to inform adaptation and a different framing is used. This centres on the urgency of short-term action that is needed in the next five-year period to help adapt to uncertain futures. It is therefore wrong to frame adaptation as two different alternative levels of effort that might be needed for 2°C vs 4°C global warming, but rather to identify what is needed today, given a wide range of outcomes are possible that span this range. Furthermore, there is an additional level of uncertainty associated with the climate models, quantified with percentile ranges such as the 5<sup>th</sup> or 95<sup>th</sup> or 10<sup>th</sup> to 90<sup>th</sup> percentiles from UKCP18 for each RCP or pathway. In the 2050s, the uncertainty from this uncertainty range is generally larger than between different emissions scenarios. Finally, it is stressed that for adaptation, time matters, i.e. it makes a big difference if 2°C warming is exceeded in 2050 or towards late century. For this reason, two time periods are considered, the 2050s and 2080s.

In the adaptation literature, this uncertainty is usually comprehensively sampled using decision making under uncertainty approaches. However, this approach is challenging for a synthesis exercise like CCRA3. Instead CCRA3 characterises the future in terms of pathways to approximate levels of global mean warming by the end of the century (2°C vs 4°C) and considers the uncertainty in the climate projections for each of these pathways. This allows sampling of scenario and model uncertainty. This broad approach is important because the evidence base for CCRA3 consists of studies that have used a number of different approaches, including different emissions scenarios and based on different climate models or projections. In order to make maximum use of the available evidence, an approach is used that allows evidence from a wide range of relevant sources irrespective of the details of specific scientific approaches. It is also stressed that any particular UK climate state could arise from a range of different emissions scenarios, depending on feedbacks in the climate system and the responses of regional climate processes within global-scale changes. For simplicity and clarity, CCRA3 uses two broad pathways to help sample the evidence. The lower pathway represents, approximately, the level of climate change if the goals of the Paris Agreement are met. The higher pathway represents the upper end of climate outcomes consistent with current worldwide policies.

**The pathway to 2°C global warming by 2100.** This is representative of stabilisation of global warming at approximately 1.5°C to 2.5°C above pre-industrial by the end of the 21<sup>st</sup> Century. This aligns to the goal of the Paris Agreement to limit warming to “well below” 2°C and “pursue efforts” to limit warming to 1.5°C. However, given the large uncertainties in regional climate outcomes related to any specific level of global warming, and the large overlap in the ranges of possible UK climate states consistent with 1.5°C to 2°C warming, a single Paris-compliant scenario is used in CCRA3, labelled the “2°C warming by 2100 pathway”. This deliberately imprecise definition of the 2°C pathway has the advantage of allowing the use of a large body of literature

on climate change impacts and risks under the RCP2.6 emissions scenario, which stabilises global warming in the range of approximately 1°C to 3°C at the 5<sup>th</sup> and 95<sup>th</sup> percentiles in the UKCP18 probabilistic projections (Box 2.5 Figure 1). The CMIP5 projections with the RCP2.6 concentration pathway stabilise at slightly lower temperatures (Murphy *et al.*, 2018).

**The pathway to 4°C global warming at the end of the century.** The higher pathway reaches global warming of 4°C at the end of the 21<sup>st</sup> Century (2080 - 2100). This represents the upper end of climate projections consistent with current worldwide policies, with the upper bound being the 95<sup>th</sup> percentile of the UKCP18 global probabilistic projections driven with the RCP6.0 emissions scenario (Box 2.5 Figure 1). RCP6.0 emissions are within the range of 21<sup>st</sup> Century emissions pathways consistent with current worldwide policies (Hausfather and Peters, 2020; also see discussion in the Introduction Chapter: Betts and Brown, 2021). NB “current policies” are distinct from the pledged Nationally Determined Contributions (NDCs) under the Paris Agreement, which would give lower emissions but which are not yet enacted in practice. When the RCP6.0 emissions scenario is used with the UKCP18 global probabilistic projections, 4°C is reached in 2080 at the 95<sup>th</sup> percentile of the projections, and in 2100 at around the 70<sup>th</sup> percentile.



**Box 2.5 Figure 1** Definition of 2°C and 4°C global warming pathways, compared with probabilistic projections of global warming with the RCP2.6 and RCP6.0 emissions scenarios from UKCP18 global projections (Murphy *et al.*, 2018), showing the 5<sup>th</sup>, 10<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup>, 90<sup>th</sup> and 95<sup>th</sup> percentile changes. Source for projections data: Met Office

### 2.6.2.2 Socio-economic scenarios

Future risks and opportunities are not just influenced by climate change, they are also influenced significantly in the future by socio-economic change (see Box 2.6). In theory, therefore, both should be considered in a national climate change risk assessment. These considerations are not trivial. Studies (e.g. Rojas *et al.*, 2013; Brown *et al.*, 2011) typically find that socio-economic change such as population or economic growth is at least as important as climate change in determining the overall magnitude of climate impacts in future periods. While the influence of socio-economics is often

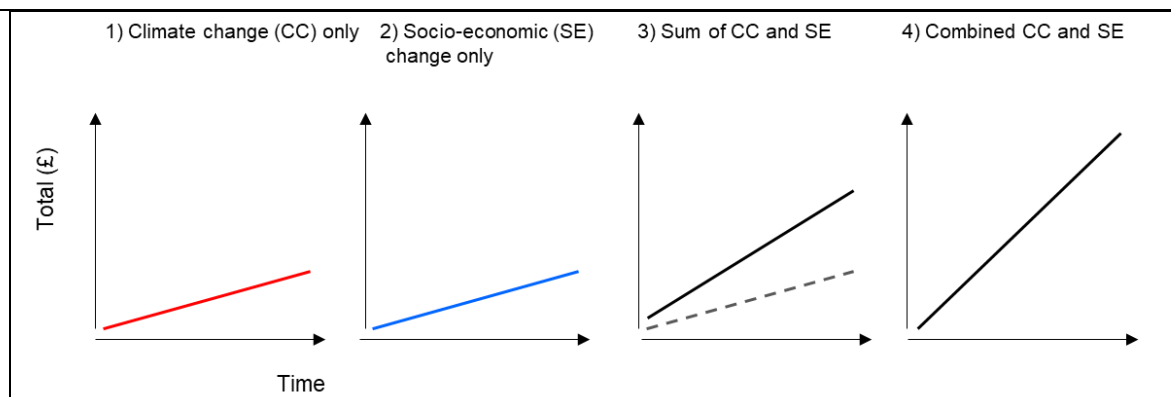
dominant at mid-century, it is still very large in the late century, as shown by studies that compare Shared Socio-economic Pathways (SSPs) (e.g. see Hinkel et al., 2014).

#### Box 2.6. Climate and Socio-economic Change.

CCRA3 should ideally take account of socio-economic change, as well as climate change, in the assessment of future risks and magnitude. A failure to do so implies that future climate change will take place in a world similar to today. The primary drivers of modelled socio-economic change include economic growth, demographic change (population) and land-use change, but there are also a wide range of other potential factors, including policy, societal and behavioural change, that are relevant, but more difficult to consider in quantitative terms. Future socio-economic change makes a very large difference to future risks, because climate and socio-economic factors can act together as risk multipliers (although it is also possible that socio-economic change can dampen impacts). There is also another dimension when considering adaptation interventions, because socio-economic change affects adaptive capacity, and therefore adaptation can be targeted to socio-economic aspects, in addition to or as well as climate risks. However, the consideration of these issues considerably complicates analysis.

Some studies look at the effect of future climate change alone, assessing the risks on the current stock (and exposure and vulnerability). This is shown using a simplified illustration (Box 2.6, Figure 1), starting with panel 1 (far left). However, in practice, even in the absence of climate change, there will be changes in exposure and vulnerability in the future, for example with the growing population projected in the UK, as well as the projected increase in economic growth. Panel 2 shows that even in the absence of climate change, future impacts could rise due to a greater stock at risk (all else being equal). However, it is not sufficient to add climate change and socio-economic together (Panel 3) because the two acting together can lead to larger cumulative risks (Panel 4, far right), e.g. climate change acts on a larger number of people or a greater value at risk (e.g. see Rojas et al, 2013). Ideally, therefore, studies should look at the future impacts of climate and socio-economic change individually as well as together, in order to separate out the relative importance of each, though in practice this is rarely considered in national risk assessments due to the difficulty of conducting this analysis across a wide range of risks.

It is also highlighted that there is considerable uncertainty around the socio-economic scenarios themselves, which adds another uncertainty dimension to risks, especially when combined with climate drivers. This can lead to a cascade of uncertainty (see Wilby and Dessai, 2010).



**Box 2.6 Figure 1** Conceptual illustration of the impact of climate and socio-economic change, individually and in combination.

When undertaking new risk or impact assessment, it is possible to include consistent socio-economic scenarios. This approach was used in CCRA1, and it was also included in the CCRA3 research projects. However, such an analysis is impossible for a synthesis exercise such as CCRA3. Furthermore, there is very little consistency on socio-economics in the underlying literature that CCRA3 synthesises, with studies using very different approaches. Some impact studies only analyse climate change effects, i.e. they assume static socio-economic conditions. Others consider both climate and socio-economic change together, but they do this differently, e.g. some consider population growth only while others also include economic growth. Only a handful of studies split out the relative contribution of climate and socio-economic change, to allow analysis of the relative contribution of each. In theory it might be possible to use UK socio-economic projections to retrospectively adjust risk and opportunity scores, but in practice, this would be extremely challenging.

For CCRA3, authors were asked to report risks and opportunities transparently and consistently from different sources used in the evidence analysis, and to document the assumptions on socio-economic change (e.g. whether UKCP09 and UK socio-economic scenarios are used, or SSP scenarios, and which parameters were considered). However, this does not address the challenge of consistently scoring risks and opportunities in the magnitude tables. Ideally, all risks and opportunities should either consistently include or exclude socio-economic factors.

For CCRA3, the recommendation was to initially identify and score the total risk (the combination of climate and socio-economic change) where possible, on the basis that it is the total risk that the UK has to adapt to, provided climate change is a major factor<sup>7</sup>, for example, the combined total effect of increased population and increased flood hazard. The exception to this is when a risk is dominated by other factors and not climate, e.g. as is the case for air pollution. In this case, authors were asked to score the incremental risk from climate change (and in the subsequent adaptation step, to only consider if the risks of additional climate-related risks were not being managed).

However, it was also recommended to split out (where possible) the contribution from climate change versus socio-economic change. In cases where risk information is only given in terms of the climate change signal alone, authors were asked to give some consideration (for future periods) of the potential change in risks (or opportunities) that might arise from the combination of socio-economic change. Most importantly, authors were asked to be transparent and document exactly what had been used, i.e. whether climate change only, or climate change and socio-economic change, and if the latter which metrics.

To help inform CCRA3, the CCC commissioned a new set of UK socioeconomic dimensions from Cambridge Econometrics (CE) (2019) as one of the CCRA3 research projects. These provided consistent projections out to 2100 for the following priority indicators: Population; Gross Domestic Product (GDP), Gross Value Added (GVA); Employment; Labour productivity (calculated from GVA

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<sup>7</sup> A different issue arises if the CCRA3 Evidence Report was to be used to provide detailed information on the benefits of domestic mitigation policy, as part of global policy commitments towards the Paris Agreement. In this case, the focus is on the difference in the total risk between alternative climate and socio-economic outcomes, e.g. between 2 and 4°C, which provides the net benefit of mitigation. However, when reporting the marginal risk of climate change impacts for an individual scenario, this should - strictly speaking - only include the marginal increase over and above the socio-economic counterfactual, as only that marginal increase is directly attributable to climate change.

and employment projections); Land use; and Households occupancy rate. It is noted that this set of data is not a set of UK socioeconomic scenarios and is not aligned to the IPCC Shared Socio-economic Pathways (SSPs). Instead, the CE projections provide a central estimate along with an upper and a lower bound estimate for each of the indicators, to use across the CCRA analysis where appropriate. The low and high socio-economic data presented are based on the ranges from the national data sets, e.g. around UK population projections. This mirrors the approach used in previous CCRA3s, which have focused on stand-alone national projections, in order to make sure that these are compatible with official Government projections. The CE projections do consider some mitigation elements for energy use, where the central scenario is based on the National Grid FES 'Two Degrees' scenario, and for land-use, where the high scenario includes an ambitious mitigation policy. It is noted that socioeconomic dimensions related to the adoption of the Net Zero emissions target was not factored into the CE report as quantified scenario data was not available, and does have some major implications, see section below. The CE socio-economic data sets were used in the CCC commissioned CCRA3 research projects on floods and water availability. However, they could not be used to adjust existing studies in the literature for the Technical Report chapters, because this would have required the primary studies to have presented future impacts for socio-economic change alone.

A final issue on the socio-economic scenarios is the linkages with the international climate change literature. In earlier studies (circa the time of the IPCC 4th Assessment Report), there was a set of self-consistent and harmonised scenarios for both socio-economic and climate change (the SRES scenarios). Future socio-economic pathways and associated Greenhouse Gas (GHG) emissions were first assessed, then fed into global and regional climate models.

For the IPCC 5th AR, a new family of scenarios was defined, the Representative Concentration Pathways (the RCPs) (van Vuuren et al., 2011). These include a set of four climate (forcing) pathways (now extended to five), which cover futures that are broadly consistent with the 2°C goal through to high-end (>4°C) scenarios. However, these were originally not aligned to specific socio-economic scenarios (as in the SRES). The RCPs were designed to be combined with a set of global Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2014). The SSPs provide a set of socio-economic data for alternative future pathways. Five alternative SSPs are currently provided (SSP1 to SSP5), each with a unique set of socio-economic data and assumptions (available for each country). The SSPs are presented along the dimensions of challenges to mitigation and adaptation. This provides the flexibility to combine alternative combinations of future climate and socio-economic futures. Combining RCPs and SSPs gives a large matrix of combinations (though not all RCP-SSP combinations are considered possible, Riahi et al., 2017). This amplifies the uncertainty envelope, and there is a need to sample possible future combinations to make analysis manageable. The RCP-SSP approach has been used in much of the International climate literature when undertaking new impacts analysis (e.g. see IPCC 2018a; IPCC, 2019). The SSPs have not been used in CCRA3, as this is not possible in a synthesis exercise, and were not considered in the CE study. However, there has been recent work that has developed Shared Socio-economic Pathways for the UK (UK-SCAPE: SPEED project) (Pedde et al, 2020). These provide downscaled and enriched versions of the SSPs for the UK as narratives and tables of trends and provide additional relevant information, which could be used as an underpinning dataset for CCRA4. These are summarised in Box 2.7 below: these descriptions are from the SPEED project itself and are presented as an illustration of this type of approach: they



were not used in CCRA3. There are also similar SSPs that have been developed specifically for Scotland (Kok et al., 2016).

#### **Box 2.7. Example of Shared Socio-economic Pathways for the UK.**

The UK-SCAPE project has developed UK SSPs. The summaries of these are presented below (Pedde et al, 2020) as an example of the development of UK specific SSPs. We stress the descriptions given below are taken from the study itself.

**UK SSP1-Sustainability.** A shift towards sustainability is triggered by natural disasters, the vulnerability of many job sectors, and worsening standards of living that are perceived to be connected to environmental degradation. Local green political networks and initiatives for change emerge, leading to strong support for regionalisation. New legislation integrates green development in lifestyle changes and in the technology, economic and energy sectors. Sustainable agricultural intensification, facilitated by effective “polluter pays” legislation, and international cooperation enable the UK to reduce its impacts from the externalities of agro-food systems. A UK-wide “green race” delivers the policies and technologies that maximise sustainability and is established across countries. Collaboration domestically and internationally plays a key role in the green race, ensuring technologies, ideas and projects are shared to gain mutual benefits. By 2100, the UK becomes a fully functional circular economy.

**SSP2-Middle of the Road.** Key public services, such as the health and pension sectors, reach a critical point prompting reform through public-private partnerships. Public-private partnerships also push forward technological development and investments in other sectors, such as transport, energy, IT and infrastructure. While the UK continues to enjoy overall economic growth, social inequalities increase and are countered by the introduction of a basic income and new working rights. A series of shocks, such as crop epidemics and severe water shortages, leads to strong policy responses that introduce Payment for Ecosystem Services schemes to address unsustainable food systems, pollution and biodiversity loss. Both urban and rural planning becomes highly regulated.

**UK-SSP3-Regional Rivalry.** With job losses and barriers to trade, the government lifts EU and UK environmental regulations to allow access to a wider supply of domestic natural resources. The UK increasingly closes its borders and invests in defence. Immigration from European and non-European countries decreases, but internal migration increases because people move around the UK in search of job opportunities which become concentrated in the major cities. The high competition for jobs leads to an exploited workforce with low salaries. With a reduction in personal income and the redistribution of public spending towards the defence sector, health prevention and treatments decrease and death rates from ill health increase. Around 2040, Scotland becomes independent from the UK, with the other nations following quickly afterwards. With increasing socio-economic barriers, conflicts arise, markets shrink and informal economies increase. With high levels of corruption, criminality is widespread across society and criminal bands substitute themselves for former institutions. Across the (former) UK, a return to self-subsistence lifestyles is widespread.

**UK- SSP4-Inequality.** In order to boost economic growth public support for radical action towards novel development strategies increases. A National Strategy Development Plan is created to foster business and economic opportunities in green energy and technological development through opening up access to land resources. As businesses and technology flourish, peer-to-peer

networks for storing and distributing digital information become popular means for businesses to bypass centralised financial regulations and accumulate wealth. Society becomes increasingly polarised and the North South divide widens. The divide is accentuated by the lack of government intervention: the welfare state has been slowly eroded until its end in the 2060s. Lack of a stable income and poor living conditions means that the vast majority live through committing minor crimes, while a small proportion of rich elite control economic and natural resources.

UK-SSP5-Fossil-fuelled Development. Reduced public support for carbon taxation and taxes to finance green transformation of infrastructure, lead to continued demand for cheaper and more readily available fossil fuels. Strong development in domestic manufacturing is supported by the discovery of shale gas, which leads to reduced energy costs. Increasing public investments in shale gas production in northern England heavily contributes to the removal of the North-South divide. The economy increases exponentially and welfare increases. Large increases in population lead to rapidly expanding “city states” and massive urban sprawl. Large-scale environmental degradation is initially masked using technological solutions. However, environmental tipping points are reached by the end of the century ultimately leading to food shortages.

The scenarios present trends for a number of key socio-economic drivers, for various categories (e.g. demography and society) and elements (e.g. population, urbanisation) for each SSP above. These scenarios are being further developed under the UKRI-funded UK Climate Resilience Research Programme, also being led by Cambridge Econometrics.

### 2.6.2.3 Net Zero

During the period that the CCRA3 was undertaken, the UK Government adopted a Net Zero greenhouse gas emissions target for 2050. The 2008 Climate Change Act was amended from *‘it is the duty of the Secretary of State to ensure that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline’* (net emission of CO<sub>2</sub> and net emissions of other targeted GHG), to *‘at least 100% lower’*. The Scottish Government also set a net-zero target date of 2045 through the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 (SP, 2019). The Welsh Government has announced a 95% reduction in greenhouse gas emissions by 2050 with an ambition to reach Net Zero (WG, 2019). At the time of writing, Northern Ireland had not yet adopted a target but this was under consideration.

This had important implications for the future baseline socio-economic scenarios in England and all DAs as well as mitigation-adaptation linkages. However, at the time of the CCRA3 analysis, there was no published Government studies or policy announcements on how this Net Zero target will be achieved. To consider this change, an additional step was included in the second round of the CCRA3 risk and opportunity scoring. This added two questions at the end of Step 1, for consideration at the level of each individual risk and opportunity. These were: 1) Is the Net Zero target likely to increase or decrease the magnitude of the CCRA3 risk/opportunity, e.g. due to the implementation of measures to achieve the target, and associated changes in the receptor the hazard is acting on? 2) Could the climate change risk or opportunity make the net zero target easier or harder to achieve? Given the current state of evidence (on Net Zero), these questions were addressed qualitatively. To inform these answers, CCRA authors were asked to draw on the techno-economic scenarios of the Net Zero report published by the CCC (CCC, 2019b). These scenarios illustrate ways in which extensive decarbonisation of the UK economy could occur by 2050 (to demonstrate that a Net Zero

emissions target by 2050 is plausible). However, these scenarios are not prescriptive on which scenario is favoured, or which policies would need to be developed to achieve the goal.

It is stressed that the CCC scenarios are technical in nature and the Net Zero target does not mean that the UK is on a SSP1 sustainability trajectory (see Box 2.7), not least because the SSPs relate to both mitigation and adaptation challenges and need to be seen in the context of global scenarios.

#### 2.6.2.4 Low likelihood, high impact scenarios

Although 4°C global warming in the 2080s is currently assessed as the fastest rate of warming consistent with current worldwide policies and a reasonably likely range of responses of the climate system, application of the Precautionary Principle motivates consideration of more extreme scenarios. The possibility of emissions growing at higher rates cannot be ruled out, and neither can the possibility of strong feedbacks in the climate system, even if these are considered unlikely.

Moreover, there may be critical thresholds at which large-scale components of the Earth's climate system, at least sub-continental in scale, switch to a qualitatively different state due to a small perturbation, and which may be irreversible (Lenton et al., 2008; Lenton et al., 2019). A number of these are particularly important for Europe (Levermann et al., 2012). Examples include Greenland and Antarctic ice sheet deglaciation, which could become irreversible even if warming is stabilised, accelerated loss of ice from the Antarctic ice sheet, collapse of the Atlantic Meridional Overturning Circulation (AMOC), and accelerated carbon release from forest dieback or thawing permafrost. The latter would affect the rate of global warming. Several of these are discussed in Chapter 1, and Good et al. (2018) provides a review of recent literature since the IPCC 5th assessment report.

In previous CCRA, there was some consideration of extreme or high-end risks associated with a High++ scenario, and this was included again in CCRA3. However, in CCRA3, there is also more attention placed on additional low-likelihood, high impact scenarios and events. These include more extreme national to local high-end risks (sometimes called tail-end), higher warming scenarios (that lead to more than 4°C global warming by the 2080s), and global Earth System tipping points or tipping elements. These have not been included in the urgency scores analysis, due to the different nature of these outcomes, but they have been considered separately.

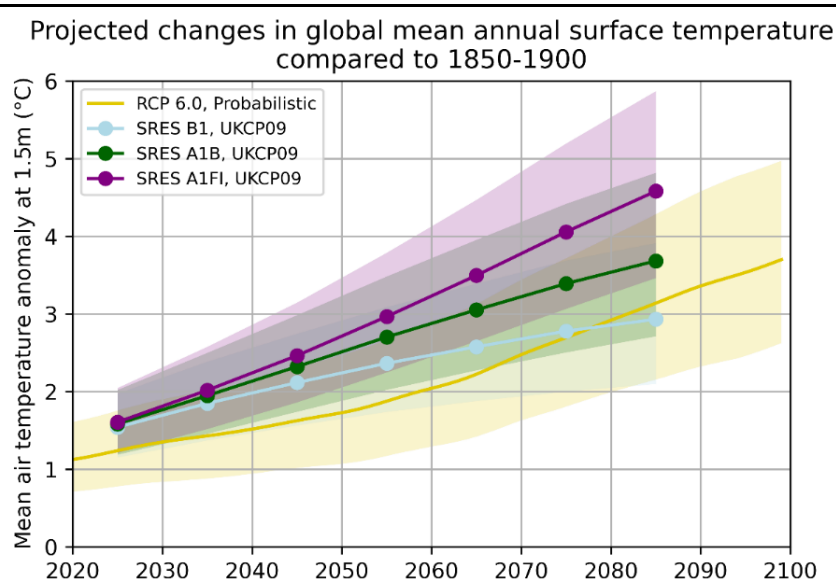
For individual risks and opportunities, authors were asked to capture and report any information on impacts of low likelihood, high impact risks in the evidence base. This could be new assessments of High++ scenarios, or evidence of impacts from projections that warm so rapidly that they reach 4°C earlier than the 2080s. The latter includes a large proportion of the UKCP18 projections with RCP8.5 emissions, and approximately the fastest-warming half of CMIP5 projections using RCP8.5 concentrations. The categorisation of different projections into the main analysis for the urgency scores versus Low Likelihood High Impacts scenarios is shown in Box 2.8. To help this, the question from the US 4th National Climate Assessment (USGCRP, 2018) was considered, i.e. 'how bad could things plausibly get?' This information was not used in the magnitude score and was reported separately.

**Box 2.8. Categorising climate projections as “Main Analysis” or “Low Likelihood High Impact”.**

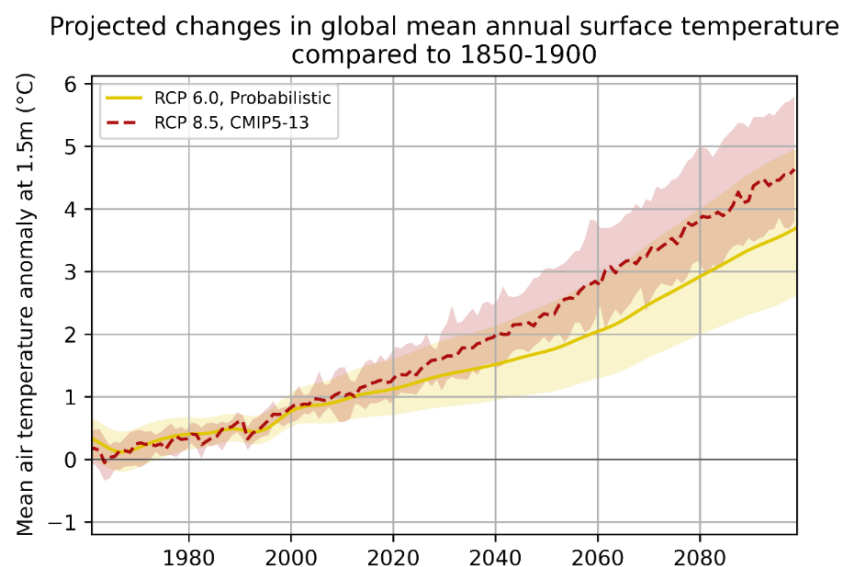
The upper boundary of the “main” projections for CCRA3 is defined by the earliest time of reaching 4°C global warming with emissions consistent with current policies (see Box 2.5). Impacts and risks studies that use projections that reach 4°C global warming between 2080 and 2100 are therefore within the “main” analysis as part of the higher warming pathway and are used for the magnitude scoring. Impacts and risks studies that use projections that reach 4°C global warming before 2080 are in the “low probability high impact” category. However, in some cases, information from the latter can still be used to inform assessments in the main analysis, e.g. by comparing results at a particular Global Warming Level (e.g. 4°C) to assess whether climate hazards or dynamical processes at a particular warming level are different in new projections such as UKCP18 compared to older projections such as UKCP09. This method works for some hazards (e.g. extreme precipitation) but not others (e.g. sea level rise).

*The following projections were considered eligible for direct inclusion in the main analysis:*

- UKCP18 projections driven by RCP6.0 emissions;
- CMIP5-based impacts studies using the RCP6.0 concentration pathway;
- Many of the UKCP09 “medium” (A1B) scenario – up to approximately the 75<sup>th</sup> percentile of the probabilistic projections (see Box 2.8 Figure 1) and the majority of the 11-member RCM Perturbed Parameter Ensemble;
- Results from the lower percentiles of probabilistic projections with the UKCP09 “high” (A1FI) scenario (see Box 2.8 Figure 1 below)
- Some CMIP5-based impacts studies using the RCP8.5 concentration pathway, including those using central estimates of the ensemble, and individual models which reach 4°C in 2080 or later (see Box 2.8 Figure 2);
- Subsets of the UKCP18 probabilistic projections driven by RCP4.5, RCP6.0 or RCP8.5 emissions that reach 4°C close to 2100 (see Sayers et al., 2020; Arnell et al., 2021);
- Subsets of the UKCP18 projections driven by RCP6.0 or RCP8.5 emissions that reach 4°C between 2080 and 2100, i.e in the upper percentiles of the RCP6.0 probabilistic projections or lower percentiles of the RCP8.5 probabilistic projections.



**Box 2.8 Figure 1** Comparison of global mean temperature projections (5<sup>th</sup> to 95<sup>th</sup> percentile ranges) from the UKCP18 probabilistic projections driven by RCP6.0 emissions with the UKCP09 probabilistic projections driven by SRES B1 (“low”), A1B (“medium”) and A1FI (“high”) emissions. Source for projections: Met Office



**Box 2.8 Figure 2** Comparison of projected global mean temperature changes (5<sup>th</sup> to 95<sup>th</sup> percentile ranges) from the UKCP18 global probabilistic projections driven by RCP6.0 emissions with the CMIP5 multi-model ensemble driven by RCP8.5 concentrations. Sources for projections: Met Office, KNMI Climate Explorer <https://climexp.knmi.nl/start.cgi>

*The following were considered part of the low likelihood, high impact (LLHI) analysis:*

- CMIP5-based impacts studies using the RCP8.5 concentration pathway with *some* of the CMIP5 global models (those that reach 4°C before 2080 – roughly half of the models);
- A subset of the UKCP18 projections driven by RCP8.5 emissions that reach 4°C before 2080, i.e. in the middle and upper lower percentiles of the RCP8.5 probabilistic projections.

Use of projections that reach 4°C before 2080

In some cases, information from projections that reach 4°C global warming earlier than 2080 were used to inform the main analysis by applying the results to a later time (e.g. HRW, 2020). A change in climate hazard at, say, 4°C global warming in 2070 could still be representative of a change in climate hazard at 4°C global warming in 2090, if the associated regional changes in climate quantities are known to depend primarily on the instantaneous magnitude of global warming and are not strongly dependent on the rate at which this magnitude is reached (Wartenberger et al., 2017; Barring and Strandberg, 2018). This allows a wider range of evidence to be included, but needs to be used with care, as it is not always scientifically appropriate – for example, this approach would not be appropriate for impacts of sea level rise, which responds to rising global temperatures over very long timescales.

Alongside this, a cross-chapter approach was taken to characterise low likelihood, high impact risks. These were discussed in Chapter 1 (Slingo, 2021). This included new information from the UK Met Office.

This information was included in an overall narrative for each chapter. It was also translated into a separate watching brief for Government for low-likelihood, high impact events and scenarios.

Finally, it is noted that the low-likelihood, high impact scenarios above relate to the earth system. There is a new emerging literature on socio-economic tipping points (van Ginkel et al., 2020), i.e. where the tipping point arises in the socio-economic system. The evidence on these extremes is more limited, which limits a more formal analysis, but some consideration of other large-scale, potentially catastrophic risks was considered in the watching brief for Government.

#### 2.6.2.5 Distributional effects and inequalities

As identified in CCRA2 (Street et al., 2016), there is strong evidence that climate risks and adaptation measures will affect people differently, depending on their social, economic and cultural environment. People and communities facing both social vulnerability and exposure to climate hazards are likely to be the worst affected, and low-income households will be particularly affected through negative effects on the cost of living, and because they have fewer resources with which to respond (JRF, 2016).

There are many different approaches for considering these issues, with elements that consider hazard, exposure and vulnerability (including adaptive capacity). In CCRA3, they are considered in terms of environmental health inequalities, recognising that socioeconomic and demographic inequalities can be expressed in relation to factors such as income, education, employment, age, sex, race/ethnicity and specific locations or settings. The report is primarily focused on how these factors affect the risk of being exposed, but also that inequalities are also caused by social or demographic differences in vulnerability/susceptibility towards certain risks.

Many environmental health inequalities, particularly where they are linked to socioeconomic variables or gender, also represent “inequities” because they are unfair and unjust. The root causes of these inequalities are complex, but involve issues of distributive justice and procedural justice (see also the definition of environmental justice, USEPA, 2020), i.e. risks are not evenly distributed within societies and populations, and different population groups may have different opportunities to influence decisions affecting their environment.

In CCRA3, chapters were asked to discuss risks or opportunities across affected populations, by type of individual, and regional dimension, and assess inequalities in relation to the impact of climate change (climate risks) (Step 1) and those generated by any relevant adaptation responses (Steps 2 and 3).

#### 2.6.2.6 Monetary valuation

The requirement statement for CCRA3 from Defra and the DAs included a request for an analysis of current and future risks and opportunities in monetary terms. This type of valuation (monetisation) is a standard part of government economic appraisal, as set out in the HM Treasury Green Book (HMT, 2018). It is based on the principles of welfare economics – that is, how the government can improve social welfare or wellbeing.

The aim of this sub-task was therefore to monetise current and future risks and opportunities (the results of Step 1a and also Step 1b below) as far as possible, expressing these in terms of the effects on social welfare or wellbeing (HMT, 2018), i.e. for society overall, as measured by individuals' preferences using a monetary metric. This values market and non-market impacts, and includes consideration of environmental, economic and social costs and benefits, not just financial costs. It is recognised, however, that it is much more challenging to value some risks, such as those in the natural environment theme. The valuation was undertaken for individual risks and opportunities.

In CCRA1, an indicative monetary valuation was undertaken. This used a consistent approach, drawing on the underlying quantitative and semi-quantitative assessment of individual risks and opportunities from the study (HRW, 2012a). It used a standardised approach for valuation, based on the guidance from HMT Green Book and from individual Government Department appraisal, and estimated the annual average damage for future time periods for the alternative UKCP09 projections for each individual risk and opportunity. Values were presented without discounting<sup>8</sup>, in order to facilitate direct comparison over time and between sectors. The monetary valuation of risks and opportunities was not undertaken in CCRA2.

For CCRA3, the method used for monetary valuation mirrors the approach used in CCRA1, and aligns to existing Government appraisal. The valuation was undertaken by a cross cutting team, working with the chapter authors, looking at risks and opportunities individually in terms of annual average effects. These estimates are presented in a separate report, but were fed back into the current and future magnitude scores for each risk or opportunity.

As CCRA3 is a synthesis of existing research, quantification of monetary values is much more challenging than in CCRA1, due to a lack of quantified future impacts for different scenarios in many cases. In CCRA1, a consistent (semi-) quantitative analysis was undertaken for each individual risk as part of a detailed impact assessment, using harmonised climate model projections and socio-economic scenarios. In contrast, CCRA3 relies on existing studies (evidence) for each risk and opportunity, but this means there is little consistency due to differences in primary studies in the choice of climate and socio-economic scenarios, methods used, granularity (national/local), etc. This makes it much more difficult to produce directly comparable results. As a result, in CCRA3 the monetary valuation was primarily indicative, providing information on the order of magnitude of potential impacts or benefits, in line with the magnitude scoring set out in Table 2.2. Where possible, the valuation analysis imposed consistent practice through use of a common base year for prices, without discounting (as for CCRA1, see above) in order to facilitate direct comparison over time and between sectors. For some risks, direct economic cost estimates were already available (primarily floods). For some quantified risks, unit monetary values from existing Governmental appraisal guidance were applied. Where no quantitative information was available, estimates of the order of magnitude of the economic costs was made based on available information and expert judgement. As well as the estimated values, a consideration was made of any important distributional costs or benefits, in line with HMT Green book guidance (HMT, 2018). It is stressed

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<sup>8</sup> It is noted that the economic costs of climate change, and the use of these estimates in subsequent policy analysis, such as the social cost of carbon or adaptation policy cost-benefit, should discount. While the choice of discount rates has been a source of considerable disagreement in the literature, there is guidance set out in the Treasury Green Book (HMT, 2018), and supplementary guidance on intergenerational discount rates (HMT, 2008).

that due to the use of a synthesis approach and evidence gaps for many of the risks, it was not possible to provide an aggregate impact (of climate change) in the UK (i.e. the total costs of climate change, from all risks and opportunities, expressed as an equivalent % of GDP).

The potential to consider the economic costs on natural capital from climate change in CCRA3 was considered, but was not possible to undertake comprehensively as it was limited by the availability of evidence on the quantitative impact (or benefit) of climate change on natural capital – as well as the valuation of changes in natural capital.

### 2.6.3 Task 1c Assessing Possible Thresholds and Lock-in

As highlighted earlier (see section 2.3), CCRA3 has made more attempt to introduce adaptive management thinking. This included consideration of thresholds and lock-in risks.

Authors were asked to identify potential major thresholds and if changes might arise under different climate futures, notably with respect to the pathways to 2°C and 4°C global warming by the end of the century, including consideration of uncertainties in regional changes. This analysis was supported by a CCC commissioned CCRA3 research project on quantifying known threshold effects in the natural environment (Jones et al, 2020). The identification of thresholds was used to consider a possible change in the magnitude score, for example when it involved a major step-change in the risk (or opportunity), although the primary use was to consider whether current adaptation plans are sufficient and whether there would be benefits from additional adaptation (i.e. Steps 2 and 3).

For lock-in, CCRA authors were asked to identify any potential for lock-in (see section 2.3) over the next five years when considering risks and opportunities. This was focused on identifying actions or decisions that could potentially increase future risk or vulnerability that are also difficult or costly to reverse later (quasi-irreversibility / path dependency). This can be from an i) action or decision taken that is 'business-as-usual', ii) from a lack of an action or decision, or iii) from a maladaptive action or decision. This introduces the concept of path dependency. Ideally, the identification of lock-in risks would involve a quantified analysis of the impacts (and costs) of inaction, though is difficult to do in a synthesis exercise such as CCRA3. Similarly, authors were asked to identify decisions or actions in the next five years that needed to be taken to enable opportunities to be realised. The temporal focus of lock-in is on the short-term, particularly the next five years (consistent with the adaptation programme period), while noting these risks or opportunities from the lock-in emerge in the longer-term. While the analysis of lock-in was identified and reported in Step 1, it was used when considering the urgency scoring in Step 3.

### 2.6.4 Task 1d Investigate Cross-Cutting and Interdependencies

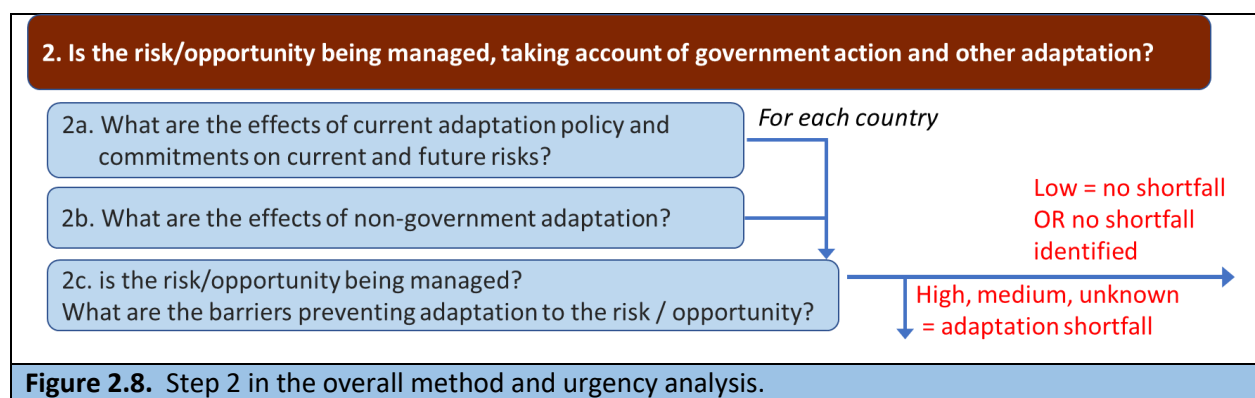
CCRA2 included a dedicated chapter on cross-cutting issues (Street et al., 2016). This considered two types of cross-cutting issues: first, cross-cutting issues related to risks which include interacting risks (hazards with multiple impacts), the consequences of interacting risks (knock-on effects) and distributional risks (how risk affects people differently); and second, cross-cutting issues related to adaptation.



For CCRA3, interdependencies, cascading risks and cross-cutting risks were considered and documented for each risk and opportunity. This analysis was supported by a CCC commissioned CCRA3 research project on Interacting risks in infrastructure, the built and natural environments (WSP, 2020). The project created 12 interlinked systems maps showing principal interactions within and between the three sectors. The analysis of interacting and cascading risks, as well as the possibility of combinations of hazards (Hillier et al., 2020) was subsequently considered in the magnitude score for each individual risk and opportunity, with authors given the option to increase the magnitude score based on evidence (using the magnitude in Tables 2.2 and 2.3).

## 2.7. Step 2 Assess Current and Planned Government and non-Governmental Adaptation

The second step in the CCRA3 Technical Report method (Figure 2.8) assesses the influence of current or planned adaptation in reducing current and future climate change risks, or responding to potential opportunities. This provides an analysis of whether the medium, high or unknown risks and opportunities identified in Step 1 are already being managed. The objective is to identify the benefit of current and announced adaptation policy in reducing risks or enabling opportunities. It also considers what might happen in the absence of further Government action, and thus whether there is a justification for additional action.



These steps are described in more detailed below.

### 2.7.1 Task 2a Analysis of Current, Planned Government Adaptation

The first task is focused on assessing how current and planned adaptation might manage the risks identified (in Step 1). The tasks involved a mix of qualitative and/or quantitative assessment methods. Authors were asked:

- To assess the policy landscape for adaptation and identify existing policies and commitments (including current as well as announced policies).
- To review and assess how far current planned adaptation action is reducing current risks or fully realising current opportunities. For risks, this included consideration of how adaptation is reducing exposure, decreasing sensitivity or enhancing adaptive capacity.

- Authors were also asked to consider and document what effect adaptation actions have had since the last CCRA, i.e. between 2012 and 2019.
- To review and assess how planned adaptation, and announced plans, could reduce future risks or realise opportunities, as well as the potential for maladaptation from these plans.

This analysis was undertaken for each country. Additional information is given below.

The starting point was to understand the organisational responsibility and governance arrangements for climate risks and adaptation (noting the two may differ), as well as to identify the current and announced organisational objectives and policies/strategies of relevance for climate risk and opportunities (non-climate and climate). This considered Government strategies and policies (overall, and in the relevant sub-programmatic areas) both in relation to specific existing and announced climate or resilience policy (National Adaptation Programme (NAP1 and NAP2) and the adaptation programmes of the DAs) but also broader policy interventions that could reduce climate risk or vulnerability. It also considered existing standards and guidance (mandatory and voluntary).

This task then considered how far existing policies and interventions are managing current risks, or fully realising opportunities. CCRA3 authors were asked to consider what effect adaptation actions have had on the level of current risks since the CCRA2 assessment (and indeed since CCRA1). Following from Step 1, it was also important to consider if current government action is addressing lock-in risks.

The analysis then looked forward, and considered how far existing policies and interventions, including announced planned adaptation policies and strategies, are managing future risks or opportunities. This effectively considered a current 'adaptation policy scenario', which included a consideration of adaptation policy objectives (and targets), the planned activities and outcomes, and the possible effect on reducing risks (or realising opportunities). This is a key part of the analysis, but it is challenging because Government targets on adaptation are often quite generic (i.e. they may not be quantitative, or defined in SMART terms [Specific, Measurable, Achievable, Realistic and Timebound, see National Audit Office, 2019]). Furthermore, there is often no quantified analysis (in published adaptation policies and strategies) on the anticipated level of risk reduction and thus the benefits of adaptation policies and strategies (Watkiss et al., 2019). In short, there is often not the quantitative evidence presented in adaptation policies to know the extent to which future risks are being reduced or opportunities realised. Further, there are important differences in how adaptation objectives can be set, as well as the framing used in policy, that have a major influence, involving the absolute or relative level of risk reduction, as well as the trade-off between adaptation costs and benefits, as well as residual risks. Further information is presented in Box 2.9.

For adaptation to future risks, the analysis considered the degree to which existing and announced policies would help adapt across all scenarios (2°C and 4°C future warming scenarios by 2100 globally) including uncertainty. Initially, authors were asked to consider whether adaptation was sufficient to manage risks across the probability range, specifically the 10<sup>th</sup> to 90<sup>th</sup> percentiles in the UKCP09 or UKCP18 projections. However, there was rarely the evidence to undertake such an analysis in practice, and authors were asked to consider the ranges of uncertainty, as far as possible.

In the case of water availability and flood risk, a current adaptation policy scenario was calculated in the accompanying CCRA3 research projects and was used directly in the relevant chapters in the Technical Report to help to consider the level of risk reduction.

Authors were also asked to discuss whether the proposed adaptation (in policies and strategies) involves potential trade-offs or maladaptation. They were also asked to consider the distributional consequences or inequalities inherent in existing or planned adaptation.

**Box 2.9 Adaptation Objectives.**

There are many existing adaptation policies in place, as reported in the NAP2 (Defra, 2018) and the 25 Year Environment Plan (25 YEP; HMG, 2018) and the Adaptation Plans of the DAs. These form the basis for generating a current adaptation policy scenario, but it is often challenging in practice to assess the actual benefits of these policies because many of them are not specific in terms of objectives (Watkiss et al., 2019). Many of the targets in the 25 YEP and NAP2 are quite general, e.g. they set a general goal for reducing risks or enhancing resilience, but do not include a specific stated objective and outcome, which makes it difficult to understand what level of adaptation benefit the policy is meant to achieve. This is important because there are different policy approaches and objectives for managing climate risks, and there is not a consistent approach used across Government for managing current risks, let alone for the future. To illustrate this by way of an example. In a hypothetical scenario of coastal protection, there are a number of potential choices for setting an adaptation objective:

- Maintain existing adaptation infrastructure. This involves additional maintenance costs in the future, but involves no additional enhancement of existing infrastructure or any additional adaptation infrastructure.
- Maintain current (policy) objectives. This aims to maintain a constant relative risk. For example, where a clear standard is set, e.g. an acceptable level of risk protection such as a 1 in 100 year level, this can be maintained over time. However, this involves cost implications, because additional infrastructure (increased costs) are projected to be needed in the future, to maintain the same (1 in 100) level of protection under a changing climate with higher risks. Importantly, maintaining the status quo will require additional action. Related to this, it cannot be assumed that Government will maintain existing objectives, unless there is an explicit policy commitment to also increase expenditure (on flood infrastructure).
- Maintain current levels of protection based on damage levels. This aims to maintain a constant absolute risk. While this looks similar to above, it involves much higher levels of protection, because of rising socio-economic change and increased value at risk, as well as increasing climate change. It therefore involves higher costs (though it also provides higher benefits).
- Maintain the (economic) optimal level of adaptation, where the costs and benefits of further protection are considered and the optimal response introduced. This usually involves lower levels of adaptation, because it avoids high-cost adaptation investments with lower benefits, but has higher residual damages when compared to risk-based approaches above (although these higher risks could, for example, be addressed through insurance). In practice, it is almost impossible to know the optimal level of adaptation because of uncertainty (though it is possible to consider dynamic optimality (Eijgenraam et al., 2013) or optimal-like responses under uncertainty).

Critically, each of these choices involve very large differences in the way that risks are managed, as well as the benefits of further action (and thus adaptation costs and benefits). These objectives would normally be compared to a counter-factual option to do nothing (to live with the risk), and would lead to the subsequent consideration of different types of interventions, e.g. whether to protect or retreat. It is highlighted that further consideration of objectives would be useful, including consideration of public risk preferences on these issues.

In theory, the analysis of planned adaptation should also take account of alternative socioeconomic futures, because these will affect exposure, residual impacts, etc. and thus the effectiveness of

adaptation. They might also bound the national and regional availability of resources for adaptation. In practice it is very difficult to assess this except where there is very detailed quantified information available. Adaptation can also – itself – lead to lock-in, linking back to the lock-in issues identified in Step 1.

A similar approach is used to assess opportunities, although there are some important differences. For opportunities, there is a need to consider spontaneous and non-government planned adaptation first (Task 2b, below) and assess how far these realise the potential benefits or whether there is a potential shortfall. In the case of the latter, the analysis has to then consider if Government action is in place to help realise opportunities, e.g. to create the enabling environment to enhance potential benefits (of climate change). If not, then the opportunity is considered not to be fully managed. In theory, this could mean that the magnitude score of a potential opportunity could be high, but current actions are only likely to deliver a low or medium score. This is different to the scoring of risks (where a low magnitude assumes no additional action is needed). The analysis of whether opportunities are being managed was primarily qualitative, based on the evidence, expert judgement and discussion with Government and stakeholders.

The analysis of planned adaptation also considered the potential synergies and trade-offs with mitigation. This has an important linkage to the Net Zero target. As highlighted above, it was not possible to use Net Zero as a new business as usual scenario, because at the time the evidence review was undertaken there were no announced plans or policies on how this would be achieved. For this reason, CCRA authors were asked to consider the synergies and trade-offs between adaptation and mitigation in Step 3, as part of Net Zero considerations (see later discussion).

#### 2.7.1.1 Adaptive capacity

Previous studies, including CCRA1, have highlighted the importance of adaptive capacity in adaptation. However, there are different definitions of adaptive capacity. From one perspective, it is a part of the IPCC Core Concepts and linked with vulnerability (see Step 1). However, there is a separate aspect of adaptive capacity that relates to the goal of CCRA3 and the capacity of planned Government action to respond to the risks identified. This emphasises socio-institutional and organisational aspects, i.e. associated with the ‘process of adaptation’ at organisational and/or structural (sector) level (see Box 2.10). This element sits within Step 2 of the method.

In CCRA1, Ballard, Black, and Lonsdale (2013) defined this form of adaptive capacity as *the ability of a system to design or implement effective adaptation strategies to adjust to information about potential climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences*. In this definition, ‘adaptive capacity’ is the capacity to take effective adaptation actions, i.e. the extent to which organisations and individuals are able to identify climate risks and make well-informed, long-term decisions that could make them more resilient to the impacts of climate change. A survey was undertaken of the level of organisational and structural capacity in different sectors. This survey was not repeated in CCRA2, and was not included in CCRA3: this represents a missed opportunity to capture progress over time. It is noted that there would be benefits from a more explicit consideration of adaptive capacity in CCRA4.

**Box 2.10 Adaptive Capacity.**

Previous work on adaptive capacity (Ballard, Black, and Lonsdale, 2013) in CCRA1 differentiated adaptive capacity into two distinct components:

- Organisational adaptive capacity (OAC): a measure of the current ability of organisations within the sector to undertake effective adaptation actions in response to climate change. This considers the level of capacity of the organisation, i.e. does it have a climate risk management or adaptation plan through to whether it is planning strategically and has implemented adaptation.
- Structural adaptive capacity (SAC): a measure of the systemic factors currently at work within the sector that affect its ability to adapt to climate change. These consider the sector's complexity, typical decision lifetimes (short or long), and the extent of activity providing potential opportunities for undertaking adaptation actions.

In sectors where SAC is low (e.g. because the sector is highly complex or decision lifetimes are typically very long), a correspondingly higher level of OAC will be needed to compensate and so enable the sector to adapt successfully to the impacts of climate change. Underlying this is the assumption that capacity develops progressively, i.e. that organisations start off less effective, but grow capacity through learning, thus barriers that apply at early stages are different to those that apply when organisations improve. There are also some studies that have reported on success factors for building capacity for adaptation (Ballard, Black, and Lonsdale, 2013; Ballard, Bond, et al., 2013; Frontier Economics, 2013).

There is also a much wider literature on adaptive capacity that includes many more components and aspects. These are contingent on the wider enabling environment, such as access to data, scientific and technical knowledge, institutions, as well as learning. A good discussion of these was included in the CCRA2 Cross Cutting Chapter (Street et al., 2016).

### 2.7.2 Task 2b Assess Non-Governmental Adaptation

The next task was to consider additional forms of adaptation that might reduce current and future risks in the absence of further planned Government or other organisational action. It assessed what additional adaptation could happen, including spontaneous and non-Governmental planned adaptation, to help manage risks (or take advantage of opportunities), but also if these non-Governmental responses had the potential for maladaptation.

For some risks or opportunities, there is a strong rationale for non-government action to lead on adaptation, i.e. where an increase in government expenditure would result in a matching decrease in private expenditure, (known as 'crowding out') (HMT, 2018).

In the previous CCRA, the consideration of this type of non-governmental adaptation (e.g. by the private sector or households) was called autonomous adaptation<sup>9</sup>. However, the focus of CCRA3 in step 2 of the method is to establish what could happen in addition to Government planned adaptation. This could include some spontaneous adaptation (i.e. reactive adaptation in response to

<sup>9</sup> The IPCC AR5 glossary (2014b) defined autonomous adaptation as a response to experienced climate and its effects, without planning explicitly or consciously focused on addressing climate change. This is also sometimes called spontaneous adaptation.

the changing climate), which might be termed autonomous. However, it could also include planned non-governmental action, such as planned adaptation by the private sector (including in privatised sectors). By definition, planned pro-active responses cannot be autonomous, irrespective of the actor, because they involve conscious plans and strategies for future climate change. For this reason, the term autonomous adaptation was not used in CCRA3.

Authors were asked instead to assess the potential for reactive, spontaneous adaptation which could arise from direct experience of a changing climate and whether these might manage risks in the absence of, or in addition to government policies and plans. This considered reactive or spontaneous adaptation as for example:

- A natural response, for example, natural species shifts to changing agroclimatic zones, or acclimatisation, for example, the physiological and behavioural acclimatisation of people to experienced higher temperatures.
- An autonomic (unplanned) response in a system, e.g. reduced winter temperatures, leading to reduced winter heating demand in households due to automatic temperature systems, reducing energy demand for heating (noting these can be defined as impact or an adaptation).
- The reactive response of households or the private sector to experienced climate change, including behavioural change (focused on the response to changes experienced, not planned, such as changing behaviour to reduce heat related risks, or fitting household level protection measures), without any Government intervention.
- The reactive market response e.g. changes in demand, etc. as a result of changing prices from experienced climate change.

It also considered planned, proactive adaptation by non-government actors, e.g. planned adaptation to future climate risks by the private sector. There is some information on private sector activities reported under the Climate Change Adaptation Reporting Power (ARP, currently going into its third round, although to note this also includes some governmental organisations as well), though this was not available at the time of CCRA3. The Climate Change Act 2008 allows the Government to ask certain organisations to produce reports on the current and future projected effects of climate change on their organisation and their proposals for adapting to climate change (though the reporting powers were changed from mandatory reporting in the first round to voluntary reporting for the second and current round). At the time of CCRA3, such reports were being prepared by a number of government agencies, authorities and regulators, as well as companies in key privatised sectors (water, energy). As highlighted earlier, this task is also important for opportunities, and the key issue in these cases is to assess whether benefits will be realised without Government action.

The consideration of additional non-Government adaptation (reactive and planned) was used to establish whether risks might be managed - and opportunities realised - even without government intervention. However, there is generally a low evidence base on non-governmental adaptation, and thus this task was primarily qualitative.

When non-Governmental adaptation is present, it is important to consider if it is beneficial, defined through the lens of social welfare, as if not this could be a form of maladaptation. Action by individual actors could, for example, shift vulnerability to others, or could lead to other impacts or disbenefits. As an example, the increase of air conditioning as a response to building overheating is a non-Governmental adaptation response, but it would increase energy use and carbon emissions,

and possibly exacerbate social inequalities (as some can afford to pay for this and some cannot), thus could be a form of maladaptation. Likewise, some farm-level responses (e.g. increased irrigation and fertiliser use) may involve wider cross-sectoral trade-offs that necessitate a role for planned intervention. This assessment also considered cases in which adaptation could have unintended consequences, e.g. creating lock-in, or increasing risks in other sectors or associated with other development or social objectives.

### 2.7.3 Task 2c Analysis of Need for Further Adaptation and Barriers to Adaptation

The final task in Step 2 was:

- To re-assess the magnitude of future risks (or opportunities), with the current and planned adaptation in place, i.e. to identify future residual risk. In general, the output of this task was to identify if risks or opportunities are being managed down to a low magnitude level, though with some exceptions listed below.
- When residual risks remained (magnitude is high, medium or unknown), to assess why action to address these risks (or take advantage of opportunities) was not being taken, i.e. to identify the barriers (constraints) to adaptation.

At the end of this task, there was a re-analysis of the magnitude of future risks or opportunities (from Step 1), taking into account planned adaptation (from 2a) and non-governmental adaptation (from 2b) identified above. This analysis was evidence based and drew on a range of independent sources, including but not limited to the CCC's progress reports, as well as emerging information on the CCC's forthcoming independent assessment of the second Scottish Climate Change Adaptation Programme.

However, in many cases, the assessment of whether current and announced policies or strategies are managing risks often involved a level of expert judgement, especially as there is little academic literature or independent analysis that evaluates the potential effectiveness of Government adaptation policy. To address this, a set of criteria were used to assess whether the risk or opportunity was being managed sufficiently. These are set out in Table 2.7 below.

A risk was only considered to be 'fully managed' if clear plans and objectives were in place, and one of the following is true:

- The planned interventions reduce the magnitude to 'low' across both scenarios of 2°C and 4°C global warming at the end of the century, as defined in Box 2.5, and across the range of uncertainty. The latter was defined in the method as sufficient to manage risks across the probability range, specifically the 10<sup>th</sup> to 90<sup>th</sup> percentiles in the UKCP09 or UKCP18 projections. However, there was rarely the evidence to undertake such an analysis in practice, and authors were asked to consider management of risk across the range of uncertainty as far as possible.
- When a current risk is medium or high magnitude now, and increases further in the future due to climate change, but planned adaptation action will manage this risk (across scenarios of both 2°C and 4°C warming at the end of the century, as defined in Box 2.5, and across the range of



uncertainty) back down to the same absolute levels of risk as today<sup>10</sup>. In this case the risk is considered to be managed provided the future strategies include clear goals and objectives for adaptation, and that the drivers of vulnerability and exposure are being well managed (today and for the future), and there is evidence that this will be delivered with appropriate implementation plans. Furthermore, to be considered fully managed, current risks (and thus residual risks in the future) also needed to demonstrate they had considered recent climate trends including potential unobserved risks today, such as captured through the UNSEEN analysis.

- When a current and future risk is dominated significantly by other factors over and above climate, e.g. as is the case for air pollution, authors were only asked to score the incremental risk from climate change in Step 1. They were then only asked to consider if the risks of additional future climate-related risks were being managed in Step 2.

For opportunities, the analysis considered whether the enabling environment (to take advantage of benefits) was in place, noting at this stage, a low score for an opportunity is a trigger for the consideration of additional action.

In all cases, the justification for this scoring was set out. This assessment (of this adaptation gap) was undertaken for each of the four countries (England, Northern Ireland, Scotland and Wales).

In cases where there was insufficient evidence, but there was widespread agreement between the CCRA authors, CCC and peer reviewers that the risk might not be managed in the future (i.e. an adaptation shortfall), then this triggered further investigation in Step 3. Conversely, if these groups considered that the lack of evidence was not an issue, e.g. because the market was considered to incentivise appropriate action or because Government has commitments in place (with reasons why), then these were not recommended for further consideration and given a “sustain current action” or “watching brief” urgency score.

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<sup>10</sup> The literature (Burton et al., 2004) identifies that adaptation to future climate will be less effective if adaptation deficits are not first addressed. If there is a medium or high current risk, this could mean there is an adaptation deficit, which could make future adaptation harder. Managing future risks only back down to this current medium or high level will also mean the adaptation deficit continues. However, it is also possible that a trade-off has been made over managing medium or high current risks based on the costs and benefits of further action versus the levels of residual risk, or based on societal risk preferences (see Box 2.7). It is difficult to judge if there is an adaptation deficit today without making a judgement on the risk appetite for addressing risks. The customer requirement from Government excluded the consideration of risk appetite in CCRA3, and thus possible issues around current adaptation deficits have not been considered.

**Table 2.6** Criteria to assess whether risks or opportunities are being managed (in the future).

	<b>Yes (fully)</b>	<b>Partially</b>	<b>No</b>
<b>Risks</b>	<p>Policy, strategy or plan in place, with clear objective (SMART) AND Actions will reduce risk to a low magnitude, across the range of future warming scenarios (2°C and 4°C at end of the century, as defined in Box 2.5, and across the uncertainty range [see text]), OR</p> <p>For risks that already have a medium or high magnitude today, actions are reducing the future risk (in the scenarios of 2°C and 4°C warming at end of the century, and across the uncertainty range) to maintain it at today's level, the drivers of vulnerability and exposure are being well managed (today and in the future), and recent climate trends are well accounted for in the policy, OR</p> <p>For risks that are dominated now and in the future by other factors over and above climate (e.g. air pollution) the incremental risk is being managed down to a low magnitude.</p>	<p>Policy, strategy or plan in place, but no clear objective.</p> <p>Or in place, but only commits to managing risk for 2°C warming pathway, or no uncertainty consideration.</p>	<p>No policy, strategy or plan in place to reduce risk, OR</p> <p>Government action or non-Governmental adaptation is managing risks as set out, but there is a risk of maladaptation, OR</p> <p>Lack of evidence of adaptation, but widespread agreement between the CCRA authors, CCC and peer reviewers that the risk might not be managed in the future.</p>
<b>Opportunities</b>	<p>Opportunity will be fully realised in absence of government intervention OR</p> <p>The enabling environment is in place to fully realise the opportunity.</p>	<p>Opportunity will NOT be fully realised in absence of government intervention and only some elements of the enabling environment are in place.</p>	<p>Opportunity will NOT be fully realised in absence of government intervention and no elements of the enabling environment are in place.</p>
<b>Confidence in the assessment of adaptation (also shown in table 2.4)</b>	<p>High: High quality evidence of the effects of future adaptation in managing the risk and high agreement between experts.</p>	<p>Medium: Some evidence on the effects of future adaptation in managing the risk and/or high agreement between experts.</p>	<p>Low: Little/no/contrasting evidence of the effects of future adaptation in managing the risk and little agreement between experts.</p>

### 2.7.3.1 Barriers

In cases where an adaptation shortfall was identified, the final task was to understand why adaptation is not taking place, i.e. what are the reasons for the adaptation gap. This builds on existing literature that identifies that there are often barriers (constraints) that make it difficult for individuals, businesses and Governments to plan and implement adaptation actions (Cimato and Mullan, 2010; Frontier et al, 2013; Klein et al., 2014). There were two considerations in this barrier analysis:

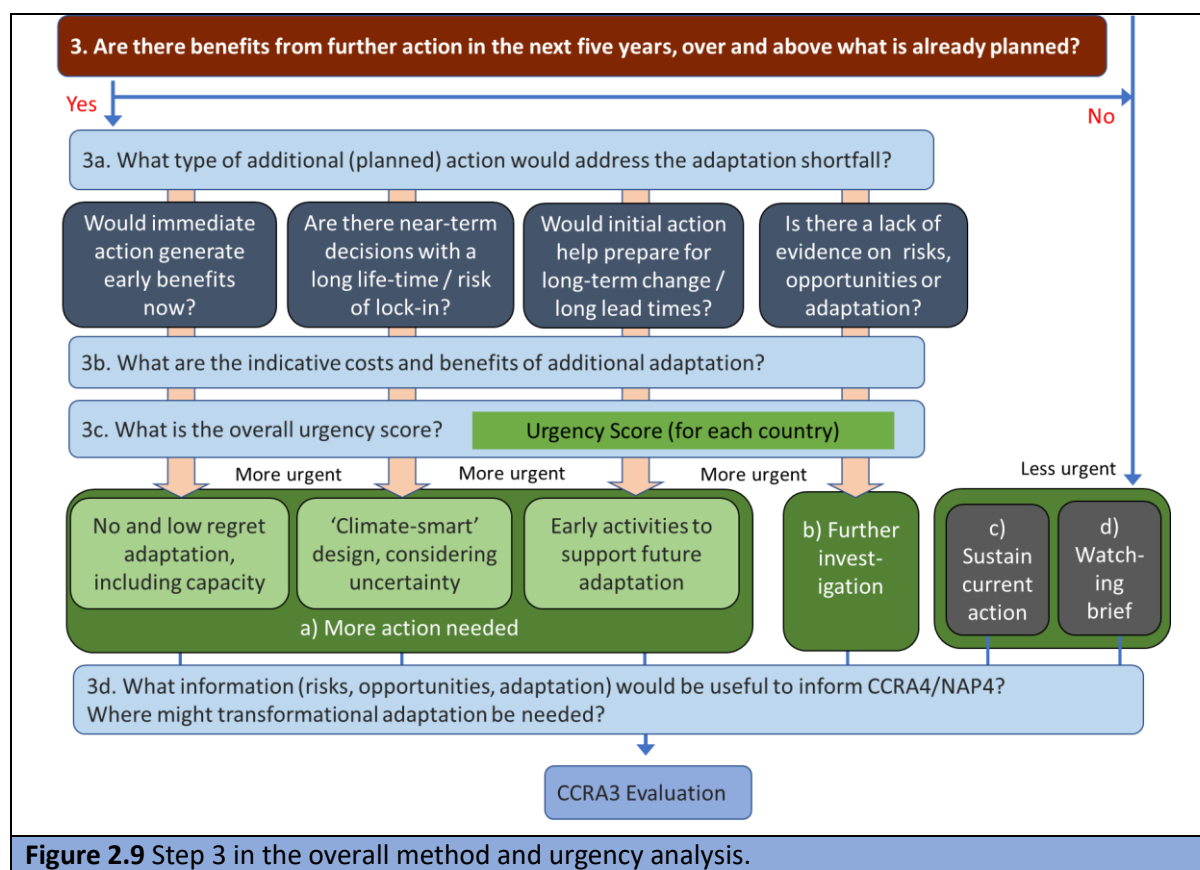
- To identify the barriers that might be stopping or hindering adaptation, e.g. market, information, policy and governance failures, behavioural barriers, etc.
- To assess how these barriers might be overcome, and thus help identify the appropriate type of planned adaptation (linked to Step 3).

These barriers and constraints are also important when considering opportunities. In many cases, the opportunities of climate change may not happen without Government providing the enabling environment, addressing the barriers that allow others to take advantage of the possible benefits.

## 2.8. Step 3 Assess the Benefits of Additional Adaptation Action

In the case where an adaptation shortfall is still identified after Step 2, i.e. the risk is not being fully managed or opportunities are not being fully realised, the final step considers the potential benefits of additional adaptation (see Figure 2.9). The aim is to identify if additional action would be beneficial, over the next five-year period, to manage the residual risks. As outlined above, CCRA3 aims to identify whether future action might be beneficial, but also what type of adaptation might be beneficial, categorised using the three building blocks set out earlier (see Figure 2.3). CCRA3 also has a new focus on understanding the scale, at least at an indicative level, of the potential costs and benefits of further action.

The findings of this analysis – along with other findings from Steps 1 and 2 – are then used to inform the overall urgency score for each risk or opportunity. CCRA3 also included a stronger linkage through to the next CCRA cycle – to CCRA4 – to identify research or information gaps that would help future adaptation (as part of adaptive management).



**Figure 2.9** Step 3 in the overall method and urgency analysis.

Chapter authors were asked to undertake the following activities for risks:

- Identify possible areas of additional adaptation - noting this could be building capacity or creating the enabling environment for adaptation, as well as delivering adaptation.
- Where possible, to suggest the type of additional adaptation that might be relevant, i.e. aligned to the three building blocks (noting that at the national level, it is likely to involve a mix of all three types of intervention). This involves linkages to lock-in risks and thresholds, and also to how adaptation might need to evolve over time considering 2°C and 4°C warming pathways.
- Assess the indicative costs and benefits of further action, as well as possible co-benefits, including synergies (or trade-offs) with mitigation (and Net Zero).
- From the steps above, to identify if further adaptation action would be beneficial.
- For all risks and opportunities (including those identified as low magnitude or being managed): Assign an overall urgency score.
- Identify additional information that would be useful to inform CCRA4/NAP4, both with respect to risks and adaptation.
- For Government/CCC, to start the process for the formal evaluation of CCRA3.

These steps are described in more detail below.

### 2.8.1 Task 3a Analysis of Possible Early Adaptation Options

The first task of Step 3 was to identify potential additional adaptation that could be undertaken to reduce risks or enhance opportunities. This was framed as the additional adaptation scenario. It

considered the broad type of adaptation that could be taken, focusing on the early adaptation priorities set out in Figure 2.3 (i.e. no and low regret options, climate-smart decisions to address lock-in, and early action to inform long-term risks or opportunities), noting that for many risks and opportunities, this may involve a portfolio across all three. In line with the mandate of the CCRA, and the advice from the Government and the DAs (in the Customer Requirement), this did not aim to define the risk appetite, or specifically on how to adapt, since those are policy or operational decisions (and thus fall to the NAP and Adaptation Programmes of the DAs). Instead, the aim was to identify potential additional adaptation interventions that were identified in the evidence and literature, as well as from inputs from chapter experts, stakeholder consultation and the peer review process. This might include direct Government intervention or by creating an enabling environment or building capacity to help others to act.

The focus was to identify additional possible action in the next adaptation reporting period (i.e. the next five years), to address risks in the current, medium or even long-term. A similar approach was taken for opportunities, except for these, it is the potential to seize an opportunity rather than avoid a negative impact that was considered. Authors were asked to consider if there were particular adaptation priorities associated with the risks of lock-in (see section 2.6.3), which would necessitate more urgent action in the next adaptation programme period. Authors were also asked where possible to consider the potential differences in adaptation that would be needed under pathways to 2°C and 4°C global warming, including uncertainty in regional impacts. These can be indicatively identified as part of a pathways approach, especially if there are potential thresholds involved (see section 2.6.3). In some cases, the difference between 2°C and 4°C warming scenarios could be a case of doing more (i.e. with higher sea level rise, there is an incremental increase in coastal protection) but in other cases, it could also mean doing something different (i.e. with higher heat thresholds, a heat alert system may not deliver the necessary adaptation to address health risks and building design may also be needed). Related to this, an important issue here was the rate of change, i.e. as well as how much adaptation action, how quickly this might it be needed. These various elements were introduced to try and encourage a more adaptive management approach, but it is stressed such considerations could only be indicative, given CCRA3 is a synthesis: much greater resources and new analysis are needed to implement adaptive management for each risk and opportunity (as found in the Economics of Climate Resilience study, HMG, 2013; Frontier et al., 2013).

Authors were also asked to consider alternative socioeconomic futures, as these will affect adaptation needs and opportunities, and also allows consideration of different adaptation options, e.g. that tackle vulnerability or adaptive capacity, rather than climate hazards directly.

This task also included a linkage to the Net Zero target, which has important implications for adaptation. CCRA3 authors were asked to consider the synergies and trade-offs between adaptation and mitigation in this task, as part of Net Zero considerations. This followed on from the questions asked in Step 1 (see earlier section) on Net Zero alignment. Authors were asked to consider if additional adaptation action might increase emissions, and thus act to make the Net Zero targets more challenging. This involves a consideration of the changes that will happen along the pathway to Net Zero, i.e. low-carbon electricity generation could reach 75-85% by 2030 (CCC, 2019b) and will be zero carbon by 2050. Conversely, additional adaptation action that had neutral or positive

synergies with mitigation – and especially Net Zero – were considered more relevant (while noting synergistic emissions reductions were not a pre-requisite for further adaptation action).

### 2.8.2 Task 3b Costs and benefits of further action (Indicative)

A new task included in CCRA3, at the request of the Customer Group, was to consider the possible costs and benefits of the further action identified in Task 3a above. As set out earlier, valuation (monetisation) is a standard part of UK government policy development and economic appraisal, as set out in the HM Treasury Green Book (HMT, 2018). It is based on the principles of welfare economics – that is, how the government can improve social welfare or wellbeing. These same concepts are applicable to the identification of possible further adaptation interventions, and the analysis of the benefits of further action. This task involved two economic elements from the Government appraisal process (HMT, 2018).

The first task in the appraisal process is to provide the rationale for intervention. HMT (2018) sets out that a clear rationale for intervention should be identified and then used to develop the objectives or outcomes the government wishes to meet through intervention. The same issues apply when considering further Government action on adaptation (Cimato and Mullan, 2010; HMG, 2013). In CCRA3, the justification for intervention was linked to the barriers identified in Step 2, i.e. the economic, policy and governance barriers that arise from market failures, or information, policy and governance failures. The rationale for intervention considered the relevant barrier or constraints involved with each risk or opportunity, and why adaptation was not already happening. This was then used to provide the economic rationale for early adaptation and some early information on what types of interventions might be appropriate.

The second task in the appraisal process is the consideration of options, starting with a long-list and then undertaking filtering this down to a short-list for detailed economic analysis. (HMT, 2018). The latter involves analysis of the costs or benefits of policies or projects (and options), where possible valued and monetised, in order to provide a common metric. In CCRA3, following from the monetary valuation of risks outlined in Step 1, this task investigated the indicative costs and benefits of the further adaptation action. This information was used to help identify the possible priority areas for action (from Figure 2.3), to assess the possible benefits of further action as compared to costs, and to help inform the urgency score. Given the synthesis nature of CCRA3, this was primarily based on a review of existing evidence and qualitative analysis.

It is stressed that the analysis of the costs and benefits of adaptation is challenging, much more so than for mitigation, and this makes it difficult to gather comparable information on further action across risks and opportunities. For mitigation, benefits are measured using a common burden (tonnes of GHG reduced), irrespective of location and sector, and many studies prioritise options using a cost-effectiveness analysis (£/tCO<sub>2</sub>), which is a relative measure and provides direct comparability across interventions. This also makes it easier to use a synthesis exercise to gather information on benefits of further action. In contrast adaptation benefits require quantification of the reductions in climate impacts (not burdens), and these are time-, sector-, location- and context-specific. Adaptation is also generally introduced as part of a mainstreaming approach in the UK, which requires consideration of multiple metrics, not a single metric, and this means that a cost-effectiveness approach is insufficient. The economic prioritisation of adaptation is therefore better

suited to cost-benefit analysis (CBA). However, because of uncertainty, as well as valuation in non-market sectors and of non-technical options, this normally requires extended cost-benefit analysis or multi-metric appraisal (see Chambwera et al., 2014).

There is also a very low evidence base on the costs and benefits of adaptation and many estimates in the literature are based on technical (engineering) adaptation options for long-term climate change (OECD, 2015). For CCRA3, however, the focus is on the costs and benefits of short-term adaptation priorities (implemented over the next five years), which might have short, medium or long-term benefits. Given the synthesis approach of CCRA3, it was not possible to undertake new analysis, and thus the task drew on previous evidence reviews (ECONADAPT, 2017) and available literature.

It is noted that the consideration of the costs and benefits of adaptation, as part of economic appraisal, does require the use of discount rates, in order to estimate the net present value or benefit to cost ratio. As highlighted earlier, the use of discount rates when calculating the social cost of carbon, or the costs and benefits of mitigation policy, has been very contentious. However, CCRA3 is not looking at mitigation policy: it is focused on domestic adaptation, particularly near-term actions that align within the existing policy decision landscape and thus existing Government recommended discounting approaches. For longer-term adaptation investments, it is stressed that the UK guidance (HMT, 2018) already uses declining discount rates. It is also noted that CCRA3 still prioritises long-term adaptation considerations, see Figure 2.3, with early action to plan for longer-term risks. However, it is highlighted that in future CCRA3s, if transformational adaptation is identified, this may necessitate consideration of intergenerational issues when considering the costs and benefits of further action (and accordingly, the HMT intergenerational discount rate scheme, HMT, 2008).

Towards the end of the CCRA3 process, in late 2020, new HMT supplementary Green Book guidance was published on accounting for the effects of climate change (adaptation) (Defra, 2020). While this was too late to inform this task (3b) in CCRA3, the approach the guidance recommends broadly aligns with the description above.

The consideration of further adaptation also considered if there were additional co-benefits. This included potential synergies (or trade-offs) with mitigation and Net Zero. Previous studies (e.g. Watkiss et al., 2015) have identified that adaptation and mitigation options can lead to synergies and potentially increase the attractiveness of adaptation, though in other cases there is also the potential for conflicts. Finally, as with Task 1a, the potential distribution of costs and benefits associated with adaptation measures was considered, i.e. to consider in broad terms who bears the costs or gains the benefits.

This information was used to assess if further action would be beneficial in managing risks or opportunities. If not, then it was categorised as a 'sustain further action' or 'watching brief'.

### 2.8.3 Task 3c overall urgency score

This task brings together the information above. It addresses the primary goal of the CCRA, which is to provide an assessment of risks and opportunities to inform the priorities for adaptation at the national level, and thus primarily seeks to provide information for the UK Government and devolved administrations.

To do this, an overall urgency score is given to each risk or opportunity. This is undertaken separately for each country. It is stressed that the urgency score provides different information to the magnitude score. For example, even if the future magnitude of a risk is classed as medium in the 2050s, the urgency might be high if plans do not exist to manage this as yet, and might be compounded if there are the risks of lock-in in the short-term. Indeed, for many future risks, there is often a window for intervention (Ballard, Black, and Lonsdale, 2013) today to change the course of action for the future.

In the CCRA context, urgency is defined as a measure of ‘the degree to which action is needed to reduce a risk or realise an opportunity from climate change’. It identifies where the need for adaptation is likely to be most ‘urgent’ between 2023 and 2027 (the next adaptation programme period) and similar periods for the devolved administrations (e.g. for Scotland, the next adaptation programme is due in 2024).

The CCRA3 urgency score follows from the previous three steps, i.e. from the assessment of 1) the current and future level of risk or opportunity, 2) the effects of current and planned adaptation, and 3) the benefits for further beneficial action in the next five years. It assigns a single urgency score for each risk and opportunity for each UK country, along with a summary of what additional adaptation could be beneficial (where relevant) and what this might look like. This simple urgency scoring approach is used because it is transparent and can be understood and considered with ease and speed by policy-makers with responsibility for large and diverse policy areas.

This urgency scoring was used in CCRA2, but some minor changes were made to the approach in CCRA3. It assigns each risk and opportunity one of four urgency scores (see Table 2.8). It is important to note that no risk or opportunity ‘falls out’ of the framework. Risks and opportunities identified as more urgent (‘more action needed’) have a specific and immediate action, but even those identified as less urgent (‘watching brief’ and ‘sustain current action’) require ongoing action and/or monitoring to see if the actions that should be happening, are happening.

Based on the urgency score, the UK Government and devolved administrations then need to decide what specific action to take to address each risk and opportunity. The effectiveness of the National Adaptation Programme for England in reducing these risks and realising opportunities is subsequently evaluated within the CCC’s statutory evaluation role. The CCC has also evaluated the effectiveness of the Scottish Climate Change Adaptation Programme in response to requests from Scottish Government.



**Table 2.7 CCRA3 Urgency Score descriptions.**

<b>Urgency score</b>	<b>Description</b>
<b>‘More action needed’*</b>	<p>New, stronger or different Government action, whether policies, implementation activities, capacity building or enabling environment for adaptation – over and above those already planned – are beneficial in the next five years to reduce climate risks or take advantage of opportunities. This will include different responses according to the nature of the risks and the type of adaptation:</p> <ul style="list-style-type: none"> <li>• Addressing current and near-term risks or opportunities with low and no-regret options (implementing activities or building capacity).</li> <li>• Integrating climate change in near-term decisions with a long life-time or lock-in.</li> <li>• Early adaptation for decisions with long lead-times or where early planning is needed as part of adaptive management.</li> </ul>
<b>‘Further investigation’*</b>	On the basis of available information, it is not known if more action is needed or not. More evidence is urgently needed to fill significant gaps or reduce the uncertainty in the current level of understanding in order to assess the need for additional action.
<b>‘Sustain current action’*</b>	Current or planned levels of activity are appropriate, but continued implementation of these policies or plans is needed to ensure that the risk or opportunity continues to be managed in the future.
<b>‘Watching brief’*</b>	The evidence in these areas should be kept under review, with continuous monitoring of risk levels and adaptation activity (or the potential for opportunities and adaptation) so that further action can be taken if necessary.

\* Note that all risks and opportunities require further research and evidence - not just those listed under further investigation - and all the risks and opportunities in this CCRA require ongoing monitoring (some form of watching brief) on risk / opportunity levels and adaptation activity. The urgency categories assigned are thus the most important priorities.

The four urgency scores have been slightly revised from those used in CCRA2. The category of ‘Research Priority’ in CCRA2 has been replaced with ‘Further investigation’ in CCRA3. This is because of some confusion following CCRA2 that ‘Research Priority’ only denoted that more research was needed, when in fact the urgency is to establish the extent to which further adaptation is required. All risks and opportunities require further research, and given the state of current knowledge, continued research is essential across all the priority risks and opportunities in this CCRA. Similarly, the greater focus on adaptive management recommended in CCRA3 means that all of the priority risks and opportunities should be monitored and measured: it is not just risks or opportunities identified as a watching brief where periodic review and updates are needed. The four urgency scores should therefore be seen as the most important element, but all should be seen as being within a package of ongoing research, monitoring, piloting, evaluation and learning.

It is highlighted that for some risks and opportunities, the lack of quantitative evidence means that expert judgement is needed to assign different risks and opportunities to the urgency categories. To

make this process robust, this was based on the consensus (through consultation and discussion) of Technical Report authors, the CCC, and the CCRA peer reviewers. The information on each risk and opportunity is set out in detail, which accompanies the urgency scores and rationale for those scores, so the reader can see transparently how these were made and can judge the urgency scores for themselves.

CCRA3 does include one additional extension on the urgency score, compared to CCRA2. When the category ‘more action needed’ is identified, then further information is presented on what form that action might take, using the three early adaptation building blocks set out in Figure 2.3, i.e. drawing on information from Task 3a and 3b above. In summary, urgent action is likely to be greater when:

- There is a high short-term adaptation shortfall (i.e. a large current adaptation gap) that provides opportunities for no and low-regret adaptation, and/or
- There is a risk of lock-in from action/inaction in the next five years, and/or
- There are benefits from early action to address major future risks.

## 2.8.4 Task 3d Learning and Evaluation – linking to CCRA4

The final task in CCRA3 is an addition to the CCRA2 method. It seeks to link the successive five-year cycles and encourage adaptive management thinking. Authors were asked where additional information or analysis would be useful to inform CCRA4 and subsequent adaptation programmes. This could be in the form of clearer research priorities, for both risks and adaptation, noting authors were encouraged to prioritise practice orientated research. It could also be in terms of other adaptive management activities, whether monitoring, piloting, learning, building capacity, etc.

Authors were also asked to summarise in a ‘looking forward’ section for each risk or opportunity some key reflections. They were also asked to address the question ‘where might transformational adaptation be needed?’. The rationale for this section was to try and encourage authors to look beyond CCRA3 – to CCRA4 and even later cycles – and identify if adaptation might need to move beyond current incremental activities. In such cases, this may involve a shift from the present-day situation where the aim of adaptation is to maintain the essence and integrity of a current system - to changing the fundamental attributes of a system itself (IPCC, 2014). It is often characterised as moving from ‘doing things differently’ to ‘doing different things’ (see Lonsdale et al., 2015; CRC, 2020). The early consideration of transformational adaptation is important, because by the time of the CCRA4, the UK will be considering actions for the period 2028-2032. If insufficient progress is made globally towards the Paris Agreement during the 2020s, it is likely that the next round of adaptation programmes (NAP4 and the AP of the DAs) will have to significantly scale-up.

Finally, following the publication of the CCRA Evidence and Government Report and the next set of national adaptation programmes, a formal evaluation of CCRA3 should be undertaken prior to CCRA4. This would provide an opportunity to review CCRA3 and introduce a stronger learning element. The results of this evaluation, along with other consultation and stakeholder feedback, should be used in the design of CCRA4. This evaluation would need to be undertaken in 2023, after the CCRA3 Technical Report, Government Report and the National Adaptation Programme.

## 2.9. References

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## Annex 1: Risk/Opportunity template (Round 1)

Templates were used for the first round of the CCRA3 methodology by authors. They were completed for each individual risk and opportunity. For the second round of the methodology, these templates were updated (and are shown below), but rather than using these, authors converted into report sections, as set out in the following chapters.

### Step 1: What is the current and future level of risk/opportunity?

#### **Current risks or opportunities**

Describe current risks or opportunities.

In addition, identify and document additional changes in the current risk or opportunity observed since CCRA1 or CCRA2.

Discuss any observed inequality of the current risks in relation to individual, place and regional dimensions (see note on inequalities description).

#### **Future risks or opportunities**

Describe future risks or opportunities.

Please report evidence that captures low and high scenarios for the mid-century and late century. Ideally this would be for time slices of the 2050s (2040–2070) and 2080s (2070–2100) for scenarios that project global warming to stabilise at  $2^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$  by 2100, or project global warming to reach  $4^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$  in 2081 – 2100. If information is not available for these time slices in projections of those rates of global warming, it may be appropriate to examine projected climate changes at global warming levels of  $2^{\circ}\text{C}$  and  $4^{\circ}\text{C}$  reached at other times, and apply these to the required dates. The validity of this will depend on whether the specific climate variables being assessed have a strong dependency on the rate of warming rather than its instantaneous magnitude, and needs to be judged on a case-by-case basis. In addition:

- Report the scenario and the time period for the evidence cited. When evidence relates to standard time slices, please document scenario and time period (e.g. RCP2.6, 2071-2100, relative to baseline period 1971-2000). When evidence is for global warming levels please document the GWL and time period (e.g.  $2^{\circ}\text{C}$  GWL, relative to preindustrial, exceeded in time period centred on 2070).
- Document the uncertainty. This should report the scenario uncertainty associated with the evidence (e.g. RCP2.6, SRES A1B, etc) and the climate model uncertainty for each scenario (e.g. 10<sup>th</sup> to 90<sup>th</sup> percentile range from UKCP09).
- Document the relative importance (where evidence exists) of the climate change versus the socio-economic drivers in the evidence reported.

Please capture and report on any tail-end risks, including low-probability high-consequence extremes (events). This could be High++ studies, or projected changes with rates of warming above the 50<sup>th</sup> percentile of probabilistic projections with the RCP8.5 emissions scenario. It may help to consider the question '*how bad could things plausibly get?*'

Discuss projected changes in risks or opportunities across affected populations, across the individual, place and regional dimensions (see note on inequalities description).

Use this information to score the magnitude (see final section).

Lock-in	Identification of potential lock-in risks, or loss of opportunities, focused on next reporting period (current, 2022 – 2027). <i>Could these affect the urgency score (link to Step 3)?</i>																														
Thresholds	Document thresholds, whether biophysical thresholds, engineering, performance or policy thresholds. Does exceedance of these vary over scenarios or across projections (uncertainty)? Please consider results of the CCRA3 Thresholds research project. <i>Could these alter the magnitude score (expert judgement and agreement across authors)?</i>																														
Interacting risks	Document interacting risks and potential size. Please consider results of the CCRA3 Interacting Risks research project. <i>Could these potentially increase the magnitude score?</i>																														
Net Zero	1) Is the net zero target likely to increase or decrease the magnitude of the risk/opportunity? 2) Could the climate change risk or opportunity make the net zero target easier or harder to achieve? (See net zero supplementary note)																														
Overall magnitude and evidence	<p>Score the magnitude using the magnitude tables, with the differentiated scoring matrix <u>for each country</u>. Report on the quality of evidence (see magnitude tables and quality of evidence table supplementary note).</p> <p><u>Score Current Magnitude</u></p> <table><tr><td></td><td>England</td><td>NI</td><td>Scotland</td><td>Wales</td></tr><tr><td><b>Magnitude</b></td><td>H /M /L /Unknown</td><td>H /M /L /Unknown</td><td>H /M /L /Unknown</td><td>H /M /L /Unknown</td></tr><tr><td>Quality of evidence</td><td>H /M /L /Unknown</td><td>H /M /L /Unknown</td><td>H /M /L /Unknown</td><td>H /M /L /Unknown</td></tr></table> <p><u>Score Future Magnitude</u></p> <p>Note that the future magnitude score is based on the highest risk or opportunity score across all scenarios and time periods, including consideration of available information on uncertainty ranges (but not including tail end risks).</p> <table><tr><td></td><td>England</td><td>NI</td><td>Scotland</td><td>Wales</td></tr><tr><td><b>Magnitude</b></td><td>H /M /L /Unknown</td><td>H /M /L /Unknown</td><td>H /M /L /Unknown</td><td>H /M /L /Unknown</td></tr><tr><td>Quality of evidence</td><td>H /M /L</td><td>H /M /L</td><td>H /M /L</td><td>H /M /L</td></tr></table> <p><i>If the risk or opportunity scores as a medium, high or unknown for current or future, progress to Step 2.</i> <i>If it scores low in both current and future, go to Step 3.</i></p>		England	NI	Scotland	Wales	<b>Magnitude</b>	H /M /L /Unknown	H /M /L /Unknown	H /M /L /Unknown	H /M /L /Unknown	Quality of evidence	H /M /L /Unknown	H /M /L /Unknown	H /M /L /Unknown	H /M /L /Unknown		England	NI	Scotland	Wales	<b>Magnitude</b>	H /M /L /Unknown	H /M /L /Unknown	H /M /L /Unknown	H /M /L /Unknown	Quality of evidence	H /M /L	H /M /L	H /M /L	H /M /L
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Quality of evidence	H /M /L /Unknown	H /M /L /Unknown	H /M /L /Unknown	H /M /L /Unknown																											
	England	NI	Scotland	Wales																											
<b>Magnitude</b>	H /M /L /Unknown	H /M /L /Unknown	H /M /L /Unknown	H /M /L /Unknown																											
Quality of evidence	H /M /L	H /M /L	H /M /L	H /M /L																											



**Step 2: Is the risk/opportunity going to be being managed, taking into account government commitments and other adaptation?**

Describe current and announced planned adaptation (including adaptive capacity).

*Who is responsible for adaptation (institutional landscape)?*

*What plans are in place or published?*

Document the changes in adaptation, and potential benefits from current adaptation, that have occurred since CCRA1/CCRA2.

*What effect adaptation actions have had on the level of current risks between 2012 and now?*

Document the potential reduction in future risks / realisation of future opportunity from the planned adaptation in place. This should also consider if government action involves potential maladaptation, or involves lock-in.

For opportunities, the steps are slightly different. There is a need to consider spontaneous and non-government planned adaptation first, and then to assess whether these actions are likely to be sufficient to fully realise potential benefits or whether there is an additional need for Government action, and if so, whether this is in place.

Is there an adaptation shortfall in planned adaptation?

Based on the analysis above, assess if there is a shortfall.

Yes/No/Unknown

To score yes, risks should be managed across the uncertainty range (but not including tail end risks).

Evidence

Document the evidence.

Quality of evidence

Rate the quality of Evidence – high, medium, low.

(see magnitude tables and quality of evidence table supplementary note – quality of evidence row 2).

Will this shortfall be addressed by non-governmental adaptation?

Will other forms of adaptation, including action by the private sector or households, reduce the risks / realise opportunities, in the absence of planned government action? Yes/No

Evidence

Document the evidence on non-governmental adaptation.

What are the barriers to adaptation?

If there is an adaptation shortfall, discuss the barriers or constraints that stop adaptation being managed .

Is the risk being managed or is there an adaptation shortfall?

Re-score the magnitude from Step 1 with information above.

Future Magnitude with existing adaptation action

	England	NI	Scotland	Wales
<b>Magnitude</b>	H /M /L/ Unknown	H /M /L/ Unknown	H /M /L/ Unknown	H /M /L/ Unknown

*If there is still a medium or high or unknown magnitude, progress to Step 3. If there is a low risk (no adaptation shortfall) with planned and other action, then go to urgency score (Sustain current action / Watching brief).*

**Step 3: Are there benefits to further action in the next five years, over and above what is already planned?**

Describe potential additional adaptation that could be taken.  
Document the evidence on possible additional actions.

This can describe possible additional adaptation, but should not be prescriptive on new policy. Ideally, please try and capture the type of early adaptation (that could be introduced in the next five-year period) and how it aligns to the 3 building blocks and linkages, i.e.:

- i) Low or no-regret adaptation (including capacity building).
- ii) Climate-smart' design or mainstreaming in early decisions.
- iii) Early adaptation activities to support future decisions and action or a combination (portfolio) of all of these.

For opportunities, this should consider additional adaptation to fully realise potential benefits (including creating the enabling environment).

What might be the additional costs and benefits of further adaptation?

Describe any observed and projected implications for distribution of adaptation (i.e. will the strategy benefit some groups/areas more than others, and/or leave others at a disadvantage?)

Are there synergies or trade-offs with mitigation and the net zero target? Does this affect the attractiveness of different types of further action?

Are there benefits of action in next 5 years?	Based on the analysis above, are there benefits of further action? Yes/No
---	--

Urgency ranking	Score urgency (into one of four scores):
-----------------	--

- More action needed.
- Further investigation.
- Sustain current action.
- Watching brief.

	England	NI	Scotland	Wales
<b>Urgency score</b>				

	Document the rationale for urgency ranking.
--	---

Confidence	Rate the quality of Evidence – high, medium, low. (see magnitude tables and quality of evidence table supplementary note – quality of evidence row 3).
------------	---

CCRA4 and transformational adaptation	What information (risks, opportunities, adaptation) would be useful to inform CCRA4/NAP4? Where might transformational adaptation be needed?
---------------------------------------	---

UK Climate Risk  
Independent  
Assessment (CCRA3)

# Technical Report

## Chapter 3: Natural Environment and Assets

Lead Authors: Pam Berry, Iain Brown

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## Key messages

A healthy, functioning natural environment is important not just for biodiversity, but also for the continued provision of key ecosystem services to the economy and to the health and well-being of our society. This chapter assesses individual risks and opportunities posed by climate change to the natural environment, whilst recognising the need to view them also from a systemic perspective.

- **More action is still needed on many risks, as the current and future projected impacts of climate change and adaptation responses are inadequate to match the scale of the risk or to realise potential opportunities** (Table 3.1). Risks previously identified as “More Action Needed” in CCRA2 include: risks to terrestrial species and habitats (section 3.3); risk to soils (section 3.6), risks to natural carbon stores and sequestration (section 3.7) and risks and opportunities to coastal species and habitats (section 3.19).
- **More action is needed if the risks and opportunities for agricultural and forestry productivity from new/alternative species are to be addressed (section 3.11).** This risk has changed from a “research priority” to “more action needed” due to increased availability of evidence on the magnitude of the risk, and the very significant adaptation shortfall, including the significant lead time to develop and implement actions in the land use sector.
- **More action is needed on the risks to freshwater species and habitats (section 3.13) and marine species, habitats and fisheries (section 3.16).** Both these risks have changed from being a “research priority” in CCRA2 due to an increasing amount of evidence on specific impacts, which suggests that the risks are already increasing and are a very likely to increase further, whilst current adaptation currently is insufficient.
- **New evidence of the potential impacts of climate change suggests risks to the natural environment from pests, pathogens and invasive non-native species (INNS) are high or increasing.** These risks relate to terrestrial (section 3.4) and freshwater (section 3.14) species and habitats, agriculture (section 3.9) and forestry (section 3.10), and to marine environments (section 3.18). These have all changed from “sustain current action” to “more action needed”, as there is increasing evidence of rising temperatures increasing the spread of pests and pathogens, with trade increasing the possibility of the arrival and establishment of INNS. The new risk descriptor Risks to marine species and habitats from pests, pathogens and invasive species (section 3.18) also concludes that there is an urgent need for “more action” to improve preparedness and address some of the key uncertainties.
- **More research is needed to improve knowledge about and awareness of the opportunities from climate change if they are to be fully realised, thus the opportunities are mostly assessed as needing “further investigation”.** These opportunities cover new species colonisations in terrestrial habitats (section 3.5), agricultural and forestry productivity from new/alternative species becoming suitable (section 3.11) and for marine species, habitats and fisheries (section 3.17). There is also a need to build adaptive capacity and to trial ways for opportunities to be fulfilled without creating risks for other species, so

that appropriate action can be taken. Opportunities for freshwater species and habitats (section 3.15) are assessed as “sustain current action”, as many of the opportunities do not directly come from climate change, but from human activities/trade. The realisation of each opportunity is closely related to the adaptation actions taken in their associated risk.

- **Risks to aquifers and agricultural land from saltwater intrusion (section 3.12) remain low.** The urgency score has changed from “sustain current action” to “further investigation” (England and Wales), as there is scope for some additional research to check assumptions on exposure and sensitivity. For Scotland and Northern Ireland, where there is a lower risk in the scale of exposure, a continued “watching brief” is more appropriate.
- **Risks and opportunities to landscape character (section 3.20)** has changed from a watching brief to further investigation of how adaptation could be effectively integrated with landscape concepts and to encourage support for the testing of policy for and implementation of such an approach.
- **Many of the risks and opportunities in the natural environment interact with the evolving Net Zero greenhouse gas emissions agenda.** Some potential synergies with adaptation actions have been identified, especially for woodland creation and peatland restoration, low carbon farming, and wetland and coastal/marine habitat and saltmarsh restoration. However, there are additional risks if adaptation, biodiversity and other factors related to wider ecosystem services are not given sufficient weight in decision making about mitigation. Good spatial targeting of the right measure in the right place is also critical and this will need to be more cognisant of the implications of a changing climate. A large increase in the area devoted to bioenergy production could present considerable risks to adaptation, biodiversity and sustainable food production, and research is needed to avoid these.
- **More integrated ecosystem-based approaches or nature-based solutions can contribute to adaptation in the natural environment and in other sectors.** This is due to the high-level of inter-relationships within the natural environment and with other sectors through the ecosystem services that it provides, including to infrastructure, people and the built environment, and businesses. Currently, implementation of these approaches in the context of climate change is limited and is not always integrated with adaptation in such a way as to realise synergies and minimise trade-offs or unintended consequences. Nevertheless, they provide a promising way forward for a more integrated and more effective adaptation that works with, rather than against, the resilience of the natural environment.
- **The risks and opportunities are assessed as increasing from now to the 2050s and the 2080s, and for 4°C global warming by 2100 compared to 2°C.** However, the limited amount of new evidence available for some risk descriptors made it difficult to assess the risk magnitude, especially across the different countries. This was compounded by a lack of clear evidence of the effectiveness of many adaptation actions, which may be related to the time taken for many of them to become effective in reducing the risk, but also because this

requires a much greater investment in systematic monitoring of indicators of vulnerability and exposure than is generally occurring at present.

**Table 3:1.** Urgency scores for risks and opportunities to the Natural Environment and Assets

Risk number	Risk / Opportunity description	Urgency scores			
		England	Northern Ireland	Scotland	Wales
N1	Risks to terrestrial species and habitats from changing climatic conditions and extreme events, including temperature change, water scarcity, wildfire, flooding, wind, and altered hydrology (including water scarcity, flooding and saline intrusion)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
N2	Risks to terrestrial species and habitats from pests, pathogens and invasive species	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
N3	Opportunities from new species colonisations in terrestrial habitats	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further Investigation  (Low confidence)	Further investigation  (Low confidence)
N4	Risks to soils from changing climatic conditions, including seasonal aridity and wetness.	More action needed  (Low confidence)	More action needed  (Low confidence)	More action needed  (Low confidence)	More action needed  (Low confidence)

N5	Risks and opportunities for natural carbon stores, carbon sequestration and GHG emissions from changing climatic conditions, including temperature change and water scarcity	More action needed  (Low confidence)	More action needed  (Low confidence)	More action needed  (Low confidence)	More action needed  (Low confidence)
N6	Risks to and opportunities for agricultural and forestry productivity from extreme events and changing climatic conditions (including temperature change, water scarcity, wildfire, flooding, coastal erosion, wind and saline intrusion).	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
N7	Risks to agriculture from pests, pathogens and invasive species	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
N8	Risks to forestry from pests, pathogens and invasive species	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
N9	Opportunities for agricultural and forestry productivity from new/alternative species becoming suitable.	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Low confidence)
N10	Risks to aquifers and agricultural land from sea level rise, saltwater intrusion	Further investigation  (Medium/low confidence)	Watching brief  (Low confidence)	Watching Brief  (Low confidence)	Further investigation  (Medium/low confidence)

N11	Risks to freshwater species and habitats from changing climatic conditions and extreme events, including higher water temperatures, flooding, water scarcity and phenological shifts.	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
N12	Risks to freshwater species and habitats from pests, pathogens and invasive species	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
N13	Opportunities to freshwater species and habitats from new species colonisations	Sustain current action  (Low confidence)	Sustain current action  (Low confidence)	Sustain current action  (Low confidence)	Sustain current action  (Low confidence)
N14	Risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures.	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
N15	Opportunities to marine species, habitats and fisheries from changing climatic conditions	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Low confidence)
N16	Risks to marine species and habitats from pests, pathogens and invasive species	More action needed  (Low confidence)	More action needed  (Low confidence)	More action needed  (Low confidence)	More action needed  (Low confidence)

N17	Risks and opportunities to coastal species and habitats due to coastal flooding, erosion and climate factors	More action needed  (Medium confidence)	More action needed  (Low confidence)	More action needed  (medium/low confidence)	More action needed  (Medium confidence)
N18	Risks and opportunities from climate change to landscape character	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Medium/low confidence)

### 3.1 Introduction

Climate change continues to affect the natural environment across the UK and so this chapter has the same general scope as of Chapter 3 in CCRA2, and correspondingly recognises the key principles of the ecosystem approach, including the interdependencies and benefits of the natural environment for the economy and broader society/human well-being, including the arts and cultural services. Nevertheless, CCRA3 has adopted a different framing of risks compared to CCRA2. Therefore, following stakeholder engagement, risks descriptors are defined based upon significant policy issues to facilitate a closer assessment of evidence in the context of policy actions. This also includes a wider inclusion of prospective opportunities as an additional component of climate change adaptation. The separation of opportunities from risks enables the potential benefits of climate change to be recognised, as well as helping refine the scoring, such that the two are not conflated. The natural environment chapter, therefore, examines the evidence of climate change organised across 18 key risks and opportunities for terrestrial, freshwater, coastal and marine natural environments, as well as for agriculture and forestry and the landscape.

The natural environment constitutes our natural capital, which directly or indirectly produces goods and services for people. It underpins provisioning services, such as agriculture and forestry, as well as water, air and soil regulation, whilst also providing opportunities for recreation and the enjoyment of wildlife and landscapes. In order to leave the environment in a better state for future generations it has been suggested that we need a transformational approach which includes a review of how we view our natural capital and measure economic success, especially for a sustainable future (Dasgupta, 2021). This natural capital is often discussed in terms of capital assets and forms part of the guidance on the risk magnitude scoring (Chapter 2: Watkiss and Betts, 2021). So, another consideration when organising the risks was to align them more closely with a natural capital approach. That is, the risks to and opportunities of climate change for terrestrial, freshwater, coastal and marine natural environments, habitats and species representing natural assets, with the others representing ecosystem services (e.g., N5 Risks to natural carbon stores, carbon

sequestration and greenhouse gas (GHG) emissions - regulating services, N6 Risks to and opportunities for agricultural and forestry productivity - provisioning services, N18. Risks and opportunities from climate change to landscape character – cultural services). This chapter examines the evidence regarding the key risks and opportunities of climate change to each of these, whilst other selected regulating services (urban cooling, pollination, water quality and soil regulation) are covered under the relevant risk.

### 3.1.1 Context and scope of chapter

There is a variable, but increasing, amount of evidence available for the assessment of the magnitude of each risk descriptor, as the chapter is based on new evidence since CCRA2, although there is less available for the opportunities. The amount available has, to a large extent, been dependent on the interest of particular risks to policy and decision makers and to the research community. As far as possible, the risks and opportunities are assessed separately for England, Northern Ireland, Scotland and Wales, as there are geographical differences in climate impacts, as well as policy contexts. However, political boundaries are not a usual unit of analysis for the natural environment, with evidence being associated with habitats, catchments, geology or soil types and so on, thus it was not possible to report on the current and future climate impacts by country. Many of the adaptation actions taken in one country are relevant to other parts of the UK, but thus far this has not been considered when assessing the risk, unless there is specific mention of such actions being applied. One constraint for the natural environment is that, while often there is a range of adaptation actions that have been proposed or undertaken, it often takes (a long) time for these actions (e.g., tree planting) to produce an effect. Also, we currently lack robust metrics/indicators and long-term monitoring to measure the effectiveness of actions for many risks and opportunities. Thus, even if appropriate long-term monitoring is in place, adaptation has not yet had a measurable effect on reducing the magnitude of the risk. In addition, while there are a range of climate change adaptation actions proposed for habitats and species, it is often very difficult to assess their effectiveness due to the complexity of response of natural systems and the fact that they are responding to various other environmental and socio-economic pressures, of which climate change is only one. Even then, climate change can exacerbate the impacts of other pressures, as is the case with wildfire (Box 3.1) which is an important cross-cutting risk that originates in the natural environment and has a distinctive climate sensitivity and changing pattern of exposure. Consistent with the ecosystem approach, we recognise that the natural environment is fundamentally interconnected and, therefore, managing individual risks (or opportunities) in isolation can have major secondary effects for other risks (both positive and negative). Thus, for CCRA3, an additional objective has been to develop a more systemic approach to highlight these inter-relationships, including to other CCRA chapters. Interacting and cross-cutting risks are considered in more detail at the end of the chapter (Sections 3.21.2 and 3.21.3). Identifying interactions has been facilitated by the Interacting Risks supporting project, which assessed interacting and cascading risks within and between the natural environment, the built environment and infrastructure (WSP *et al.* 2020). They found that the natural environment was the most frequent recipient of risk flows from other impacts. However, it is important to realise that these interactions mean that the natural environment also can contribute to adaptation across risks and in other sectors, for example through the use of nature-based solutions.

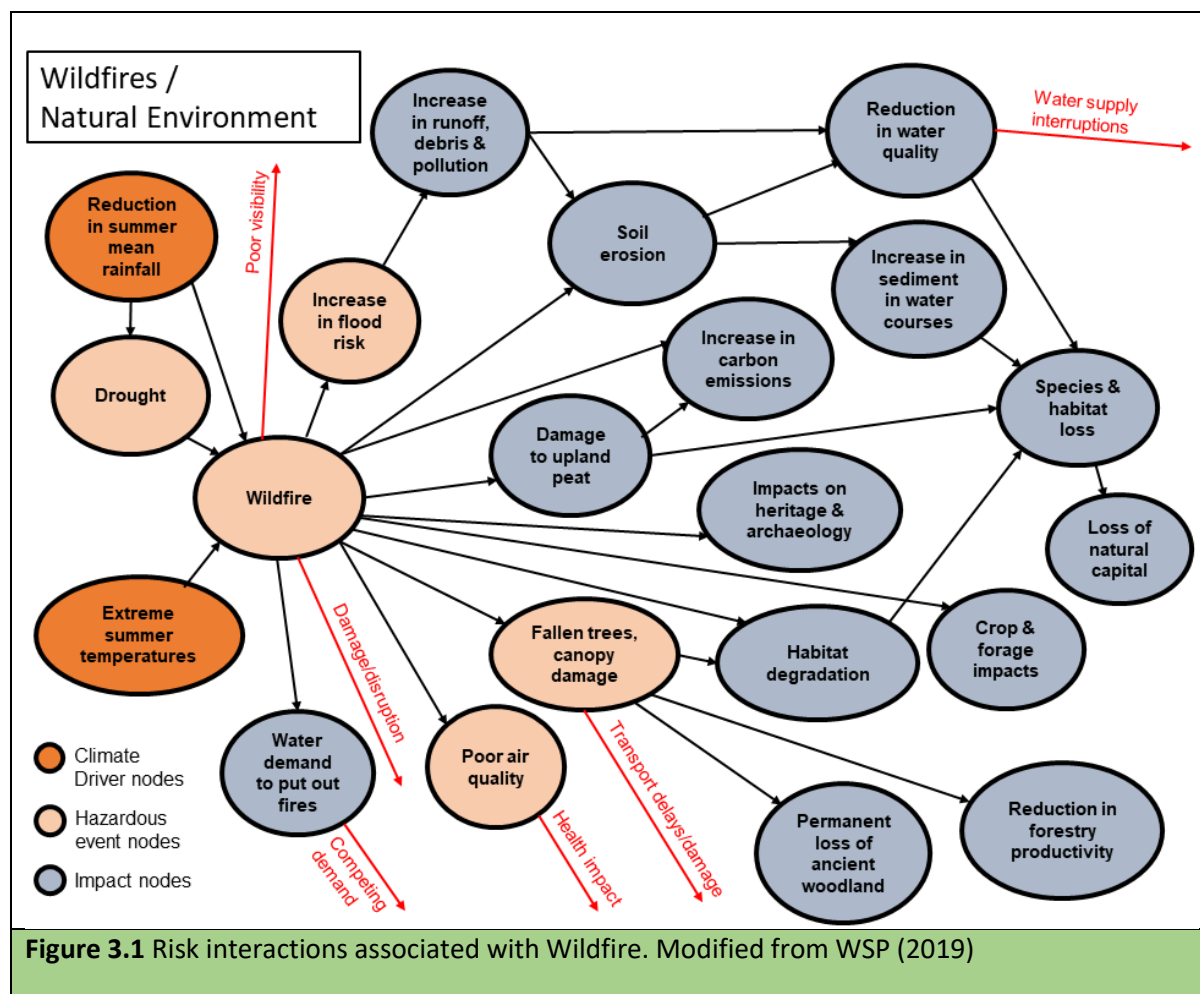
### Box 3.1: Wildfire Risk

- Wildfire occurrence is episodic with events linked to the occurrence of dry or hot weather and fuel availability from vegetation, plant litter and soil organic matter.
- A wildfire 'season' with distinct peaks in spring and summer can be recognised from event data (Belcher *et al.*, 2021).
- The vast majority of wildfires in the UK are a result of human agency (deliberate or accidental) rather than from lightning strikes.
- Analysing current trends in annual wildfire occurrence is difficult due to limited long-term data (standardised incidence reporting only occurred since 2008 and can still be of variable quality) and their episodic frequency which means considerable interannual and multi-year variability (Davies and Legg, 2016; Belcher *et al.*, 2021; Costa *et al.*, 2020; Glaves *et al.*, 2020). Analysis to update the CCC Adaptation Indicators (ADAS, 2019) in England reported that for 2009-2017, 130,370 wildfire incidents were recorded, burning an area of 35,557ha. Mountain heath and bog made up around half of this area, with improved and semi-natural grassland and arable land making up a further 40%. It found a strong correlation between wildfire incidence and drought conditions, consistent with reports of spikes in wildfires during such periods. For example, sustained dry weather in July 2018 in Northern Ireland required the Fire and Rescue Service to attend an unprecedented number of gorse fires (1,061; a 1053% increase on the same period in 2017).
- Despite these data challenges, there is some evidence for an increase in wildfire size and severity in recent years, and indications for an earlier start to the wildfire season (Belcher *et al.*, 2021).
- Analysis has suggested that the use of the same threshold values throughout the UK underestimates wildfire danger in the cooler parts of the UK, hence more recent work has used variable thresholds based upon percentiles (De Jong *et al.*, 2016).
- Wildfire climate modelling uses a concept of wildfire danger to characterise meteorological risk factors and to distinguish them from other trigger factors associated with ignition (fuel load, human agency etc.). The combination of these factors defines wildfire risk.
- Future modelling using climate change projections (UKCP18 or CMIP5) suggests a significant increase in summer wildfire danger but only a slight increase in spring (Belcher *et al.*, 2021; Perry and Vanvy, 2021; Arnell *et al.*, 2021).
- Future modelling also indicates that the highest risk areas will be in south/east England but that the change in risk may be most pronounced for UK locations in the north and west that currently have a rather lower present-day risk (Perry and Vanvy, 2021 Arnell *et al.*, 2021).
- Headline indicators of fire danger based upon threshold exceedances vary depending on indicator, but average number of danger days increases 3-4 times by the 2080s (compared to a 1981-2010 baseline) (Arnell *et al.*, 2021). In addition to changes in temperature and rainfall patterns, reductions in relative humidity have an important influence.
- In addition to severe consequences for the natural environment (see Risks N1, N4, N5, N6, N18), wildfire can also have notable detrimental effects for the built environment and human health (Chapter 5: Kovats and Brisley, 2021), also including impacts on transport infrastructure (Chapter 4: Jaroszweski, Wood and Chapman, 2021), and businesses (Chapter 6: Surminksi,



2021) (Belcher *et al.*, 2021). There are also notable cross-sectoral risk interactions which can occur through wildfire events (see Figure 3.1).

- Responsibilities and governance of wildfire risk is rather variable across the UK and in different regions, including lack of clarity on lead organisations for co-ordinating adaptation actions and overall strategy. There is often limited evidence that awareness of changing risk has been incorporated into risk management, including a tendency towards a reactive rather than proactive approach, which can constrain adaptive capacity (Gazzard *et al.*, 2016; Moffatt and Gazzard, 2019).
- Prescribed burning of moorland has for a long time been used as a traditional management practice. Important differences regarding biodiversity and ecosystem services can occur due to differences in intensity between shallow and deeper burns and on diverse habitats (including peatland), which highlight the importance of good practice (Belcher *et al.*, 2021). With regard to risk reduction, it is therefore crucial that good practice is further adapted to be consistent with the changing risk from climate change, as informed by further research and knowledge exchange.
- The Fire and Rescue Service's (FRS) Integrated Risk Management Plans (IRMPs) and local strategies need further development to include climate change.
- An improved system for fire danger and other risk factors, specific to UK conditions, would enhance risk assessment, including use in scenario planning.
- Regional and national wildfire forums can have an important role in improving awareness through knowledge exchange on changing risk magnitudes, good practice, and cross-sectoral initiatives, although their role is advisory (Gazzard *et al.*, 2016).
- There are important interactions between the Net Zero agenda and changing climate risks for wildfire which are yet to be fully assessed and included in planning strategies.
- Wildfire risk is included in the National Security Risk Assessment (NSRA), but this requires further consideration of how climate change is incorporated in risk profiling, including links to the CCRA, consistent with planning for a reasonable worst-case scenario (UK Parliament POST, 2019). In addition, there is concern that the NSRA does not fully consider impacts on the natural environment, including loss of ecosystem services.



CCRA3 follows on from the publication of UKCP18 climate scenarios and associated studies (see Chapter 1: Slingo, 2021), and the further insights these provide are highlighted where possible. However, relationships between the natural environment and climate data are typically complex, and in some instances difficult to generalise especially when based upon limited examples, therefore advances based upon UKCP18 remain work in progress. Thus, for many risks, they may confirm our confidence in direction of travel, but without further evidence we have low confidence in the outcomes in quantitative terms. The natural environment is not just affected by changes in mean annual or seasonal climate parameters, but also by more extreme events. CCRA3 has sought to identify these Low Likelihood High Impact events and their possible consequences (Box 3.2).

### Box 3.2: Low Likelihood High Impact (LLHI) Events

The natural environment is also exposed to infrequent high magnitude events that occur at the extremes of climate change projections (see Chapter 1: Slingo, 2021). Some links have already been suggested between extreme climatic events and population crashes and explosions for birds and Lepidoptera in England (Palmer *et al.*, 2017). Even small changes in frequency or magnitude may have profound implications for resilience and adaptation planning. These events can be

especially damaging because of the occurrence of thresholds and tipping points in natural systems and their myriad interconnections, beyond which systems reorganise around different connections and properties that also affect ecosystem services provided to humans (see section 3.20.3). Four distinctive examples are highlighted to demonstrate the importance of LLHI events.

Firstly, and quite probably the most severe risk to the natural environment as a whole, would be from the occurrence of a severe and sustained drought occurring over a large part of the UK. In synoptic terms, this is typically associated with an extended phase of anticyclonic ‘blocking’ that acts to exclude sources of rainfall for a considerable duration, or even for multiple phases of blocking across consecutive seasons as occurs when a dry summer follows a dry winter. The latter situation can act to deplete groundwater reserves that require winter rainfall for recharge, hence both surface and groundwater reserves become severely depleted during summer (and even into autumn). In addition, very high soil moisture deficits and resultant feedbacks through reduced evapotranspiration can further exacerbate and perpetuate drought severity. Analysis of UKCP18 shows that, despite ongoing uncertainties regarding drought prediction, the possibility of this scenario is increasing (Chapter 1: Slingo, 2021) and that enhanced soil moisture droughts are a specific high-risk category.

The consequences for biodiversity (terrestrial and freshwater) and for agriculture and forestry from such an event scenario would be very severe, but possibly further compounded by cross-sectoral conflicts over water availability because such a scenario would challenge existing procedures and plans (e.g., ‘drought orders’) and would involve the interaction of multiple CCRA3 risks together. In addition, such a situation may potentially lead to a significantly increased risk of large-scale wildfires for which contingency planning appears to be limited.

Secondly, agriculture, and especially intensive arable cropping and horticulture, is particularly vulnerable to combined negative effects of anomalous seasonal variations. As discussed for Risk N6, an unprecedented and unforeseen catastrophic wheat harvest occurred in the ‘breadbasket’ regions of France in 2016 due to the unusual combination of an anomalously warm autumn followed by a wet spring, conditions which are also projected to increase in future (Ben-Ari *et al.*, 2018). As recent years have shown, the UK is also vulnerable to poor harvests: reductions in yields reduced the export value of wheat by 73% and 84% in 2017 and 2018, respectively, and increased the import expenditure by 38% and 79% (DEFRA, 2019a); in addition, wheat production in 2020 was down 40% on 2019 values, primarily due to the previous wet autumn/winter. Much of the UK’s current arable and horticultural land area is in east and south-east of England but recent joint probability analysis of the spatial coincidence of combined hot, dry and wet extreme events has shown that this region is most exposed to the likelihood of such combined events over recent decades (joint probability values of 0.69 to 0.99: Dodd *et al.*, 2020), although further work is required to assess risk for a specific growing season.

With projected trends towards an increased likelihood of wetter winters and hotter drier summers (UKCP18 and other projections), there is an increased joint probability of a scenario arising where negative impacts from consecutive bad seasons accrue and are compounded throughout the crop growing period, resulting in major losses in crop production. In such a situation, the UK becomes more reliant on overseas imports but if large-scale atmospheric

teleconnections also mean that other important agricultural production areas are also negatively affected at the same time, then there may be potential consequences for food security (see Chapter 7: Challinor and Benton, 2021). These challenges for agriculture are further exacerbated because the UK population is increasing and therefore more food will be required to feed the country (notwithstanding potential diet changes, food waste reduction etc.).

Thirdly, the prevalence of sustained storm conditions throughout a season or longer period can have severe consequences for coastal environments as noted in Risk N17. This is typically associated with a vigorous westerly (zonal) circulation, typically associated with a positive North Atlantic Oscillation during the winter months or a longer period. For example, the winter season of 2013/2014 was the stormiest on record for the British Isles (Priestley *et al.*, 2017) with an unprecedented amount of cyclone clustering corresponding to an average of one intense cyclone affecting the country every 2.5 days. These persistent cyclonic conditions were associated with a strong and straight upper-level jet stream flanked by Rossby wave features breaking on both its northern and southern sides for the duration of the clustering event. For the coastal environment, continued presence of storm conditions in winter 2013/14 with large amounts of wave energy caused major erosion and flooding, which then takes many years for habitats and species to recover from. With the increased likelihood of such severe winter cyclonic conditions increasing in future projections provided by UKCP18 (Chapter 1: Slingo, 2021), in combination with higher water levels from ongoing sea-level rise, there is the increased prospect of passing a threshold where existing coastal systems are unable to recover and reconfiguration of vulnerable habitats and ecosystems occurs, with both loss of areas of high biodiversity value and loss of coastal ecosystem services (Section 3.21.3) (see also Chapter 4: Jaroszweski, Wood and Chapman, 2021). These implications also extend to the marine environment, where shallow-water habitats such as seagrass beds and serpulid reefs are vulnerable to an increased pattern of storm frequency that over-rides their natural recovery time between time events (section 3.16.1).

A fourth example can be identified with particular importance to the marine environment due to expected changes in ocean circulation. The Atlantic Meridional Overturning Circulation (AMOC) transports large amounts of sub-tropical water into the higher latitudes of the North Atlantic. Although AMOC exhibits considerable variability, future projections indicate sustained slowdown as downwelling zones in the Arctic that drive the circulation become fresher and also due to changes in the tropics (Liu *et al.*, 2020). This large-scale circulation is intricately linked to other ocean currents that have a strong influence on the temperature and salinity of the seas around the UK, with major implications for the future of marine ecosystems (McCarthy *et al.*, 2020). Most notably at higher magnitudes of climate change, this also increases the likelihood of increased instability and volatility in AMOC, although the dominant atmospheric effect will continue to be a strong warming trend (as shown by UKCP18 and other projections). While a complete shutdown of the AMOC and associated severe cooling of NW Europe (as occurred at the transition from the last glaciation) is considered very unlikely this century, it remains a plausible outcome in the next century (Chapter 1: Slingo, 2021). Nevertheless, significant weakening of the AMOC is considered likely and the latest generation of models project stronger weakening than previously projected, with a possible AMOC decline between 34% and 45% by 2100.

Similarly, further utilisation of future socioeconomic scenarios (for example, based upon the IPCC SSP framework) are at an early stage. Much of this chapter, therefore, is based on studies using UKCP09 or IPCC climate scenarios and relatively few apply socioeconomic scenarios. Thus, it has not been possible to determine the contribution of climate versus socio-economic drivers on the magnitude of the risk or opportunity.

Social and economic trends also are relevant to the future risks from climate change and can influence future magnitude through changes in exposure and vulnerability (see Chapter 2: Watkiss and Betts, 2021). A new consistent set of UK socio-economic projections has been produced for CCRA3 (Cambridge Econometrics, 2019) which include projections of land-use, land use change and forestry activities in the future, “taking into account current land use policies and/or aspirations (e.g., achieving a certain percentage of forest cover by 2050)”. The central projection assumes current policies and funding, non-forest rates and 2014 afforestation planting rates continue at the same rate into the future, although this planting rate is very low (e.g., for Scotland and does not reflect current policy/practice). These projections do include a high scenario, which assumes ambitious levels for afforestation, and full restoration of peatlands. Since these projections were produced, the UK has adopted a Net Zero target (see below). However, there is comparatively little evidence available on the implications of the Net Zero target for some risks, although it is more relevant for those related to agriculture and forestry.

Socio-economic factors also can influence adaptation, in terms of the capacity to act, but again there is generally a lack of evidence on the amount they can contribute. They can also affect the adaptation options considered and implemented, such as afforestation and peatland restoration, nature-based solutions including natural flood management and coastal realignment. Cultural drivers, such as community practices, values and past experiences also may affect the perception of climate risks and adaptation options and responses. For some risks or opportunities in this chapter there are additional factors from changes that occur internationally, especially in sectors where there is international trade. These issues are discussed further in Chapter 7 (Challinor and Benton, 2021) on international risks.

A further development for CCRA3 has been assessment of climate risks and opportunities as they interact with the evolving agenda for Net Zero greenhouse gas emissions (GHG). This is particularly distinctive for the natural environment because of its capacity to sequester carbon, therefore acting to balance other GHG emissions, which include agricultural sources for the land use sector. The CCC report on land use and policies for achieving Net Zero suggested land use options which included increased tree planting; encouraging low-carbon farming practices; restoring peatlands, encouraging bioenergy crops and reducing food waste and consumption of the most carbon-intensive foods (CCC, 2020). It should however be noted that the scope for the natural environment to offset emissions in other sectors is a small fraction of current emissions and is not a replacement for emissions reductions. Chapter 3 identifies some of these options under individual risks, while the synergies and potential trade-offs that will be important for enhanced integration of adaptation actions with the Net Zero agenda are discussed further at the end of the chapter (Section 3.21.1).

The UK Government has put several new Bills before Parliament that will replace existing environmental legislation arising from the UK leaving the EU. The devolved administrations are also involved in developing replacement policies/strategies for their countries e.g., for agri-environment

support. These, together with their associated policies and strategies, will have implications for the risks in this chapter even if climate change is not directly part of their considerations. The desire for a green recovery from Covid-19 similarly would also have implications for the natural environment. The £40 million Green Recovery Challenge Fund in England (which has been increased by a further £40 million), for example, could provide some funding of adaptation for the natural environment, through the themes of nature conservation and restoration or nature-based solutions (Box 3.3), particularly focused on climate change mitigation and adaptation, such as tree planting and restoring peatland, wetlands or coastal ecosystems. Whilst the other theme, connecting people with nature, could help wider engagement with adaptation.

Throughout the chapter the assessment of risk magnitude is primarily based upon expert opinion as supported by review and evaluation of the available evidence. This is consistent with the generic CCRA methodology but recognises the inherent challenges when applying this method to the natural environment which involves both multifaceted risks together with complex systems and processes. The challenge is especially pronounced when interpreting evidence providing quantification of risks which typically only provides a partial assessment of the overall risk, and therefore requires further qualification in the context of the policy-based risk descriptors used to define the chapter structure. For CCRA3, little or no evidence was found of the additional costs and benefits of further adaptation, although many of the risks do suggest that further adaptation is needed.

### Box 3.3: Nature-based solutions

- Nature-based solutions (NbS) are: “actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham *et al.*, 2016).
- NbS include green and blue infrastructure for protecting, sustaining or restoring nature, thus supporting conservation actions. Green and blue infrastructure are an increasingly important adaptation measure and generate a range of benefits both for wildlife (e.g., through habitat creation) and human health (e.g., reducing the Urban Heat Island effect, providing shading and surface water flood resilience; providing recreational opportunities; as well as potentially improving air quality).
- NbS can be used to address a range of environmental, social and/or economic challenges in both urban and rural areas and should provide benefits to human well-being and to biodiversity.
- As NbS involve working with nature, which is multi-functional, they lead to many other co-benefits in addition to the intended outcome(s).
- NbS, therefore, are sectorally cross-cutting and, in the context of CCRA3, interact with other risks and adaptation options.
- In the UK, NbS in particular have been considered for climate mitigation (helping to achieve Net Zero). They are also being implemented as part of adaptation to current and future flooding, where they have been shown to be as, if not more, effective than grey infrastructure for smaller scale flood events (EA, 2018a).
- Currently they have been less explicitly implemented for adaptation for species and habitats, but many ecosystem-based adaptation actions could be considered NbS (Cohen-Shacham *et al.*, 2019). Many NbS are currently quite small scale and need scaling up, in the way that is being considered for climate mitigation (e.g., widespread tree planting), in order for them to make a greater contribution to climate adaptation. They are also often context specific, and this is an issue when trying to scale up to the landscape level. Basing

NbS on an understanding of habitat function should allow a system-scale approach, for example in coastal habitats.

- NbS often are cost effective compared to alternatives, but less is known about their maintenance costs (Keesstra *et al.*, 2018).
- Climate change will impact on the ecosystems and their species in NbS and thus there is a need to ensure that they are resilient to future climate change if they are to continue to provide the functions and benefits which make them a solution to a particular challenge.

### 3.2 Risks to terrestrial species and habitats from changing climatic conditions and extreme events, including temperature change, water scarcity, wildfire, flooding, wind, and altered hydrology (including water scarcity, flooding and saline intrusion). (N1)

- The magnitude of current and future risks is considered to be large due to the number of species and habitats adversely affected by climate change, both now and in the future.
- There is a range of policies and measures aimed at facilitating adaptation and reducing the impacts of climate change on terrestrial habitats and there are good examples of habitat restoration, which would be expected to build resilience to climate change.
- However, there is a lack of evidence of the effectiveness of these measures to date, while a range of indicators show ongoing declines in biodiversity, which leave species and habitats more vulnerable to climate change impacts.
- There are also few examples of adjustments to manage climate change impacts for the best biodiversity outcomes, when building resilience is not enough to prevent change.
- Several initiatives exist that may reduce climate change risks, but they are not yet finalised and will need to be adequately resourced if they are to make a difference. Thus, the risk is assessed as more action needed.

Since the last CCRA, our understanding of climate change impacts on terrestrial biodiversity has increased, but it has not changed the broad picture of risk and there has been little progress in reducing the factors that increase vulnerability. There is now considerable evidence of the current and likely future effects of climate change and associated drivers on individuals (e.g., their physiology and phenology), populations (composition and abundance) and species (distribution). These combine to affect community and habitat composition and thus the services that they can deliver (Risks N6 and N18). These changes can lead to losses or gains of species in a community or geographic area, whilst changes in distribution can represent threats or opportunities for the receiving area (Risk N3). Risks are therefore different for different species and habitats but given the potential for local or more widespread extinctions and losses, the current and future risks are both assessed to be high magnitude across the UK, with high and medium confidence in the evidence. There is a range of policies and measures aimed at facilitating adaptation and reducing the impacts

of climate change and there are good examples of habitat restoration, which would be expected to build resilience to climate change. However, there is a lack of evidence of the effectiveness of these measures to date, while a range of indicators showing ongoing declines in biodiversity which leave species and habitats more vulnerable to climate change impacts. There are also few examples of adjustments to manage climate change impacts for the best biodiversity outcomes, when building resilience is not sufficient to prevent change. There are a number of initiatives that may reduce climate change risks, but they are not yet finalised and will need to be adequately resourced if they are to make a difference. Thus, the risk is assessed as more action needed.

### 3.2.1 Current and future level of risk (N1)

Note: currently available evidence is not sufficient to allow us to report on the current and future level of risk for each UK country separately.

#### 3.2.1.1 Current risk (N1)

Risks to species from climate change are species-specific. Vulnerability is affected by a wide range of factors, including both the intrinsic attributes of the species and the condition and extent of the habitats where they live (Oliver *et al.*, 2015). Some species are likely to disappear from areas where they are currently found; those at their southern range margin are at highest risk of being lost from parts of their current range as a result of rising temperatures. About a third of studied species are in this category (Pearce Higgins *et al.*, 2017), including many northern species such as the mountain ringlet butterfly and alpine ladies mantle (Natural England and RSPB, 2020). Some species may retreat to higher altitudes (Hubble, 2014; World Museum Liverpool, 2016)

Much of the evidence on movements of range margins comes from more mobile species like birds. Massimino *et al.* (2015) found that, for 80 breeding birds in the period 1994-2009, the leading edge had moved northwards at 3.3 km year<sup>-1</sup>, while the trailing edge had remained largely static. Gillings *et al.* (2015) analysed the range shifts of the distributions of 122 species of British breeding birds during 1988–1991 and 2008–2011 and full range of directional axes. They estimated a 13.5 km shift northwards (see Risk N3), but also a retraction of southern margins. They concluded that the range shifts were multidirectional, individualistic, and probably determined by species-specific interactions of multiple climate factors, with a consequence for change in community composition.

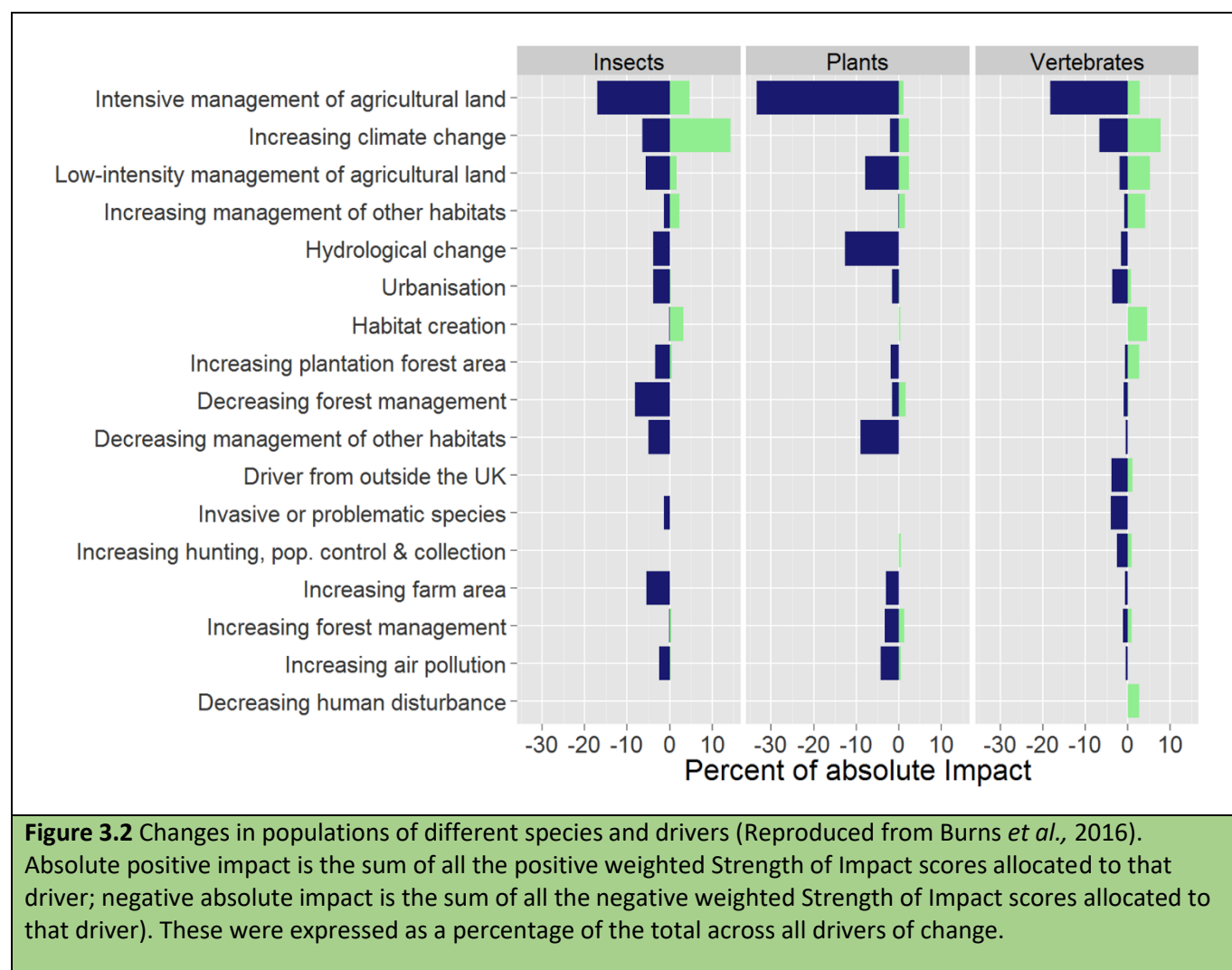
There is new evidence of changes in the balance of different species in communities with southern species tending to increase and /or northern species declining. Climate change may be a contributing factor to the decline of some upland birds (e.g., curlew - 65% decline between 1970 and 2015 across the UK; golden plovers -31% decline 1995 to 2015 in Scotland) through the drying of soils negatively affecting food supplies in their breeding grounds (Hayhow *et al.*, 2017). Also, to the decline of boreal vascular plants, but not boreal bryophytes in southern Britain (Hill and Preston, 2015). Warmer, drier conditions during the spring and summer are potentially adversely affecting food availability and abundance for long-distance migrants e.g., ring ouzel. Changes in bird community composition are mostly affected by the decline in cold loving species (Hayhow *et al.*, 2017), whereas for butterflies it is related to the increase in southern warmth-loving species (Oliver



*et al.*, 2017). In Scotland, overall moth abundance (based on 176 species) decreased by 20% (1975–2014) and by 46% (1990–2014), although their distribution (occupancy) has increased (Dennis *et al.*, 2019). The increasing distribution is likely to be driven by a warming summer climate facilitating range expansion, whereas population declines may be driven by reductions in habitat quality, changes in land management practices and warmer, wetter winters.

There is new evidence of the impact of extreme events, particularly droughts, which are likely to increase in frequency with climate change. At a European scale, Thompson *et al.* (2020) detected a reduction in net carbon uptake (Net Ecosystem Exchange) of ecosystems during the extreme drought of 2018. There are also demonstrable impacts on species and communities with new evidence on the observed impacts on butterflies (McDermott Long *et al.*, 2017, Palmer *et al.*, 2017). While Palmer *et al.* (2017) suggest that extreme climatic events (approximating to low frequency high magnitude events such as heat, drought, flooding) can be associated with some population crashes and explosions of birds and butterflies in England, but that species show individualistic responses.

Species may be affected not just by mean or extreme changes in climate, but also by other drivers acting separately or in combination with climate. A literature and expert-based review of the drivers of change assessed the strength of their impact across 322 species sampled from a broad range of taxonomic groups in the UK (Burns *et al.*, 2016). Each driver was scored by experts on a 1 to 12 scale according to their estimation of its strength of impact on the species and each Strength of Impact score was weighted as if the same number of species had been assessed for each higher taxonomic group (vascular plants, vertebrates and invertebrates). They found that that overall species' population change (~1970–2012) has been most strongly impacted by intensive management of agricultural land and by climatic change (Figure 3.2). The former had the biggest impact on all three taxonomic groups (insects, plants and vertebrates), whilst climatic change was the second biggest for vertebrates and insects, but only the seventh biggest impact on plants. The identified impacts of climate change were a mixture of positive and negative effects. Some of the other drivers were associated with particular groups, for example, the negative impact of hydrological change was relatively greater for vascular plants, whereas the positive impact of habitat creation was relatively lower.



Habitat availability has been shown to be important for species movements at range margins. Platts *et al.* (2019) found that for 13 invertebrate taxonomic groups in Britain, while climate is an important factor in range shifts, half of the variation in rates of range shift could be explained by the interaction between habitat availability and climate change, with habitat availability explaining more of the between-species variation in poleward movement. Also, habitat generalists are expanding more quickly than specialists, but this may be affected by the type of habitats at or beyond the range margin and by the species requirements. Land use is another driver affecting species. Fox *et al.* (2014) found in their examination of the frequency of occurrence of 673 macro-moth species in Great Britain that species with a trailing range margin in northern Britain declined. This is consistent with climate change, but widespread species, which were predicted to be more sensitive to land use than to climate change, declined significantly in southern Britain, where the cover of urban and arable land has increased. Also, moths associated with low nitrogen and open environments declined most strongly, which is also consistent with a land-use change explanation.

Wildfire can result in serious damage to or loss of habitats and species, which may show varying degrees of recovery (Kelly *et al.*, 2016). Climatically, wildfire is linked with hot, dry conditions (ADAS, 2019), but in the UK most wildfire is started by people, as a result of accidental ignition, while the climatic conditions are a predisposing factor. Its incidence is particularly associated with improved

grassland, arable land and woodland (CCC report, 2019; Welsh Government, 2019a), while Arnell *et al.* (2021) identified it with lowland and upland heath. In peatlands and woodlands, it can lead to the release of large amounts of stored carbon.

Coastal habitats around the UK are being affected directly by climate change, as well as indirectly sea level rise, increased saline intrusion, coastal erosion and accretion (Burden *et al.*, 2020) and are covered in risk N17. About 17% of the UK coastline is currently affected by erosion, whilst other areas are either stable or accreting (MCCIP, 2020). These changes are partly driven by sea-level rise, but also by extreme storm events. Habitat loss as a result of 'coastal squeeze' where hard sea defences prevent inland movement of habitats is occurring widely around the UK coast, particularly in low-lying areas with soft rock geology, such as East Anglia.

Climate change is also affecting the phenology (timing of life cycle events) of a range of species, with many (but not all) spring events occurring earlier and autumn ones later (Newson *et al.*, 2016; Donnelly, 2018). This can have consequences for population numbers, ecological processes and food webs. For example, a selection of 130 butterfly and moth species responded positively to ~0.5°C spring warming (1995-2014) in terms of earlier adult emergence, with increases in population growth for species with multiple generations a year, but with neutral or negative effects for those with only one generation a year (Macgregor *et al.*, 2019). The different responses of species also have the potential to lead to mismatches in timings, such as food demand and availability, while lengthening of the growing season could affect productivity and carbon sequestration (Donnelly *et al.*, 2015).

Pollinators are an important group of species for agricultural production, as well as for wild plants. Like many other species, they face multiple pressures, from habitat loss, pests and diseases, extreme weather, competition from invasive species and the use of some pesticides (Vanbergen, 2014; Goulson *et al.*, 2015). Climate change is interacting with these pressures, but the challenges of disentangling climate drivers from multiple stressors means the evidence for its impact remains limited. Modelling using distribution records for 353 hoverfly and bee species, based on 715,392 biological records collected by the UK Hoverfly Recording Scheme and the Bees, Wasps and Ants Recording Society showed that in Great Britain between 1980 and 2013 a third of wild pollinator species (33%) have decreased over this period, approximately a tenth have increased, with the remaining species showing no clear trend (Powney *et al.*, 2019). These losses appeared to be particularly associated with rare species. There was a 55% decline among species associated with uplands in contrast to dominant crop pollinators, which increased by 12%, potentially in response agri-environment measures. The general declines are likely to lead to a deterioration in both wider biodiversity and non-crop pollination services. As noted in CCRA2, climate change is already influencing the range, abundance, and seasonal activity of some pollinator species (Steele *et al.*, 2019). There is increasing evidence of the spring advancement, although increased winter temperatures are affecting queen bee survival. The index of the timing of biological spring events (number of days after 31 December) shows that since 1998, the annual mean observation dates have been around 8 days in advance of the average dates in the first part of the 20th century (Defra, 2020a). Seasonal changes and extreme climatic events could potentially lead to mismatches in plant and pollinator life cycles, to the detriment of both plants and pollinators and the provision of pollination services (Steele *et al.*, 2019).

### 3.2.1.2 Future risk (N1)

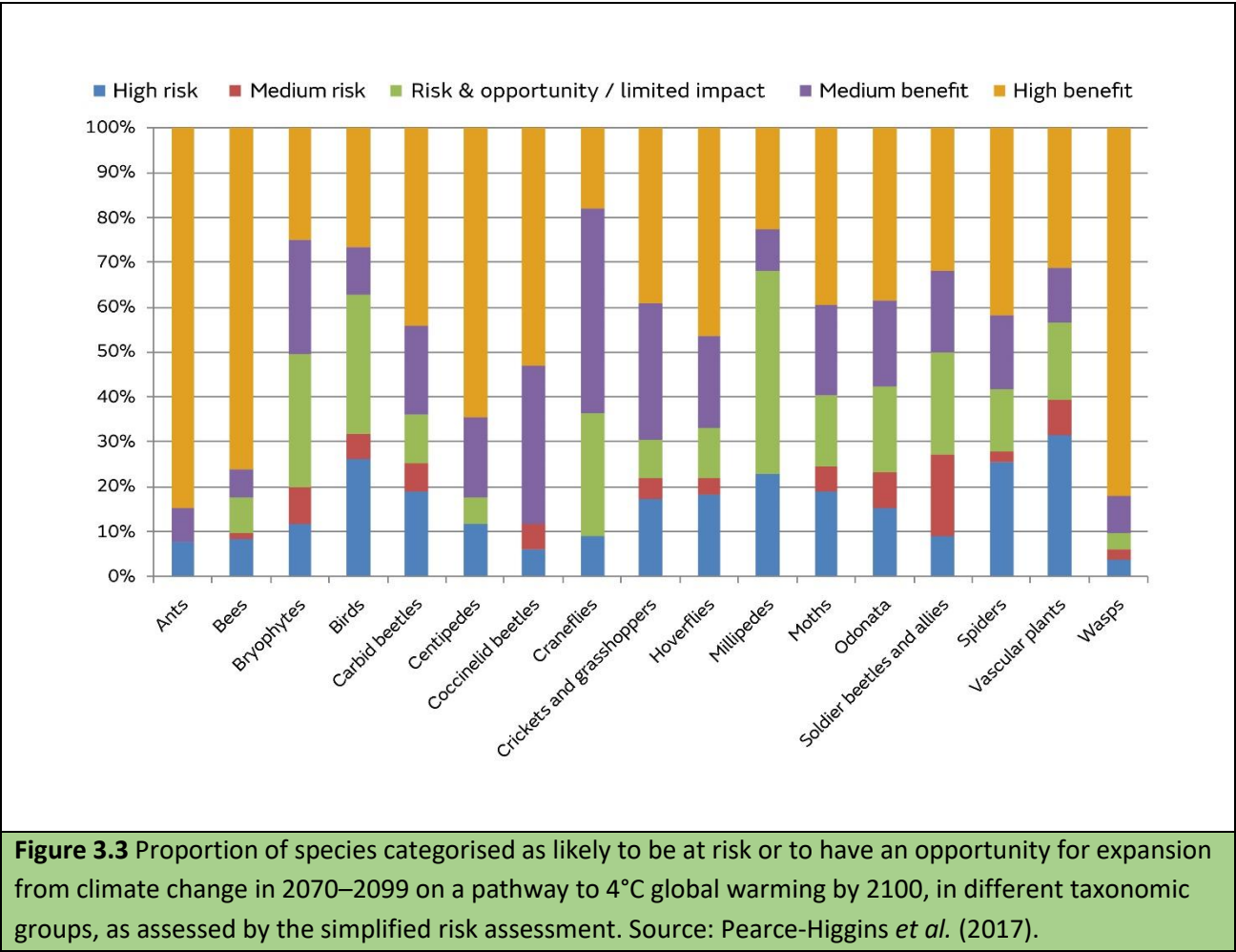
A wide range of studies have shown that impacts are likely to increase over the next few decades at least, under all plausible emissions scenarios. It is important to note that many ecological changes take place over long-timescales and with intrinsic time lags (Watts *et al.*, 2020), so processes that are already taking place will result in inevitable ecological changes in the coming years. The larger the change in climate, the larger the impacts, with the potential for far reaching effects which will be hard to adapt to, if global greenhouse gas emissions do not reduce quickly and significantly.

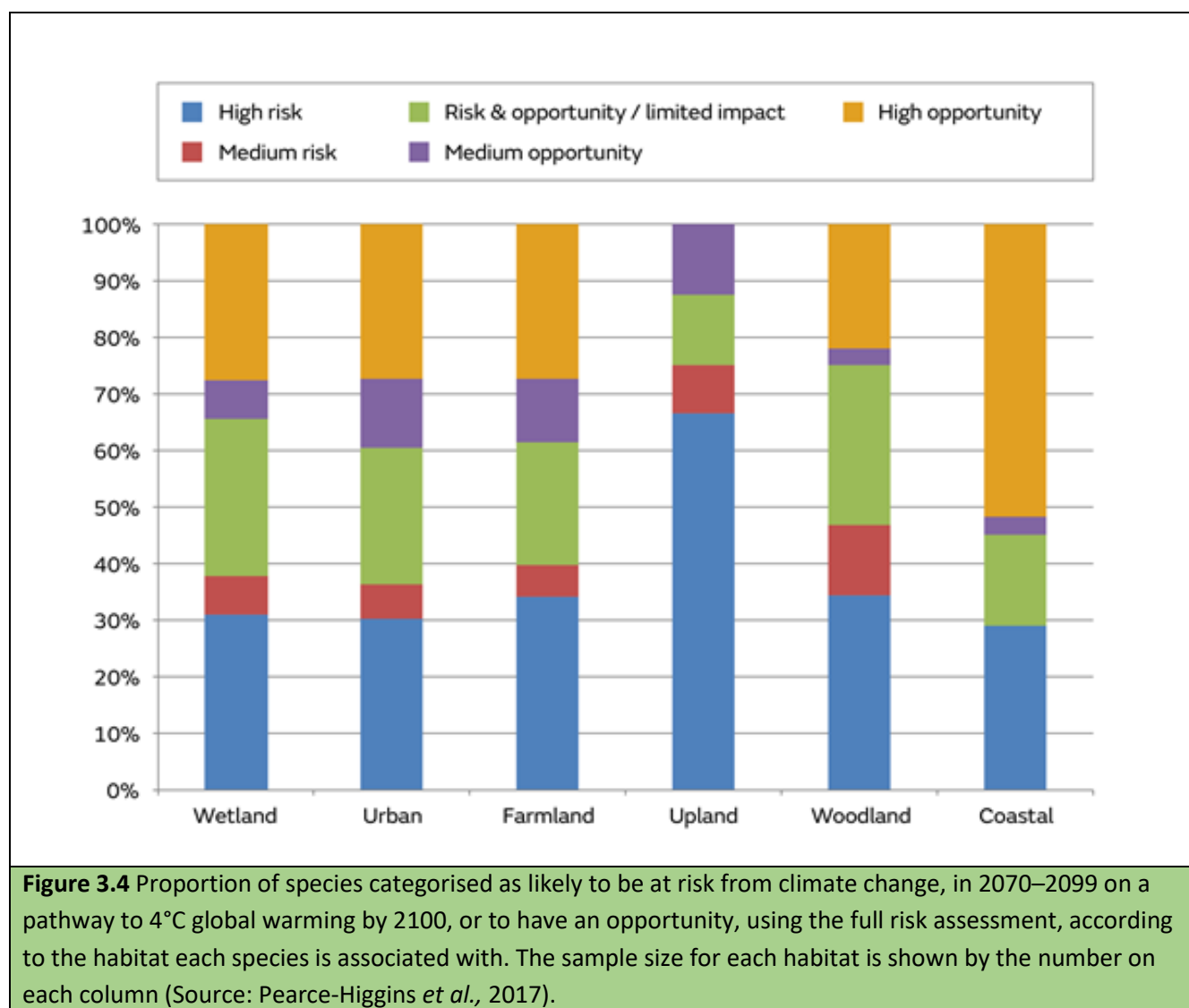
The scale of change will be heavily dependent on the ability of species to physically disperse and adapt to changes in average temperatures, rainfall patterns and seasonality. Many species will only be able to acclimatise or adapt naturally (autonomously adapt) to changing climatic conditions if there is a coherent network of habitats available to them that are in a good ecological condition. Some with low mobility will not be able to shift locations and for some isolated populations e.g., montane, very rare species, dispersal is not possible. There is the potential for genetic adaptation and phenotypic plasticity (Lancaster *et al.*, 2017), but this is unlikely to be sufficient at higher rates of climate change for many species (Parmesan and Hanley, 2015) and some species are likely to be lost. Conservation translocation, in particular assisted colonisation, therefore, may become an increasingly significant tool for some species where natural colonisation is not possible (IUCN SSC, 2013).

A simple assessment of 3048 species using climate envelope modelling and a scenario of approximately 4°C global warming by 2100<sup>1</sup> found that in England, 28% were at risk of range loss by 2070-2099, whilst 54% could have an opportunity to expand their range (Pearce Higgins *et al.*, 2017). A more detailed full assessment of 402 species, included ecological information, such as dispersal and habitat availability, and some species of conservation concern, found that 36% were at risk of range loss, whilst 41% may expand their range. A taxonomic analysis of the risks and opportunities showed considerable variation between groups, with many insects, for example, ants and wasps, showing high levels of projected opportunity, whilst bryophytes and vascular plants had more species at risk (Figure 3.3). Habitat-wise those most at risk were upland species adapted to cool conditions, with a projected decline in suitable climate space for 75% of the species (Figure 3.4).

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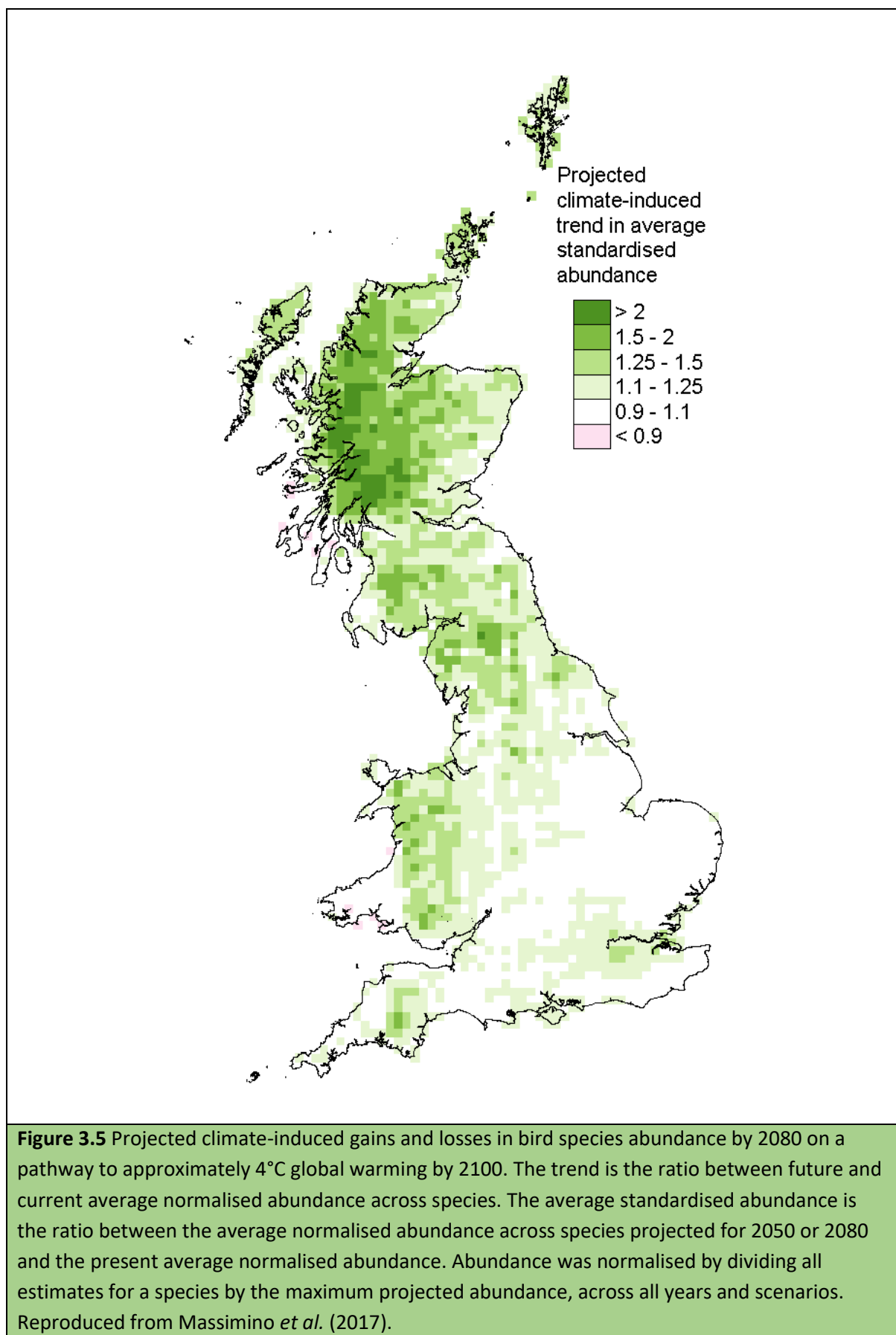
<sup>1</sup> UKCP09 medium scenario (SRES A1B)

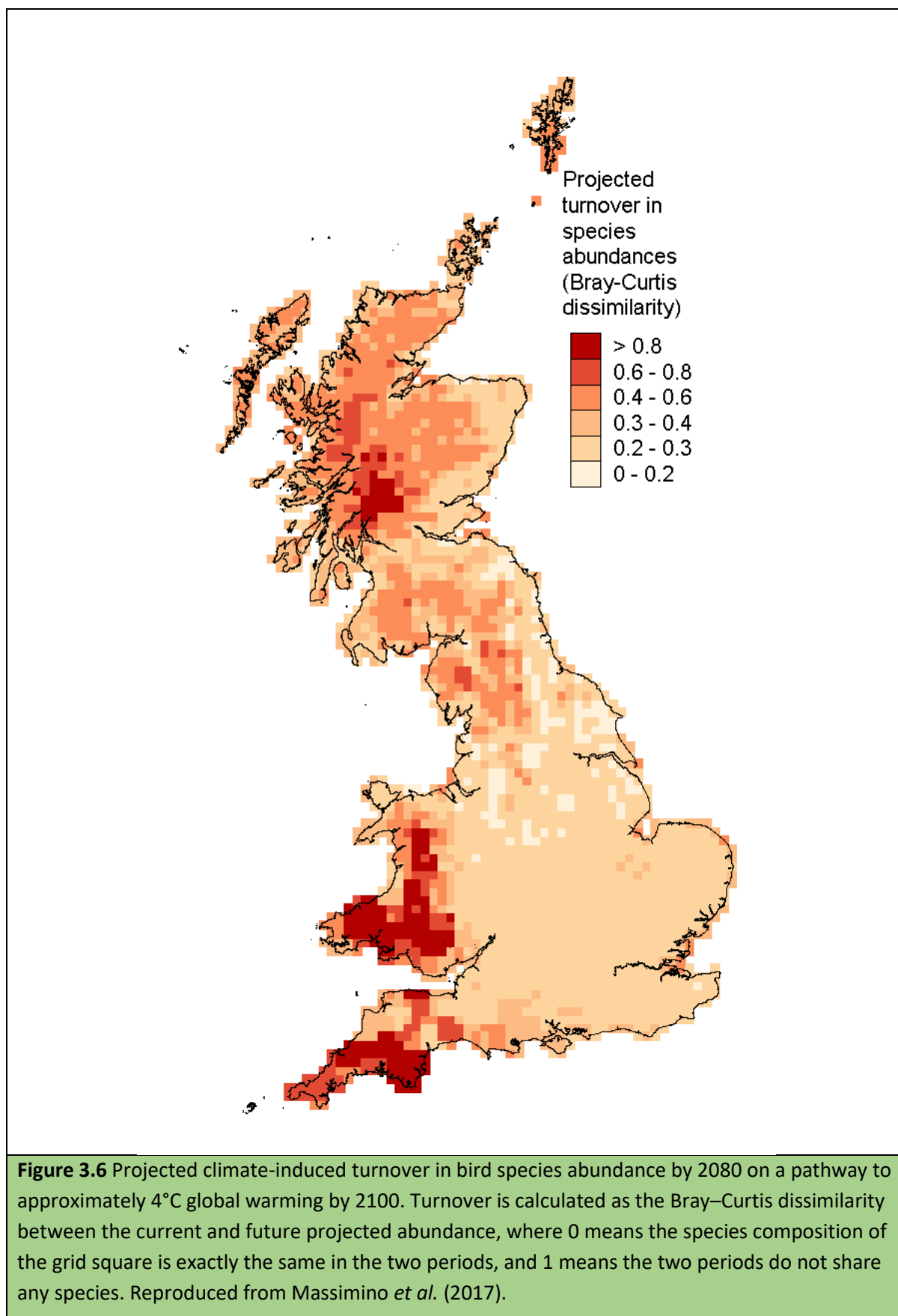




There is however new evidence that these risks can be lower in refugia where topography creates greater variation in the microclimate (Maclean *et al.*, 2015; Massimino *et al.*, 2020). For species at risk in areas that experienced the highest rates of warming, extirpation risk was reduced by 22% for plants and by 9% for insects where refugia were present (Suggitt *et al.*, 2018). Modelling of changes in suitable climate for birds under the future 3°C-rise scenario, combined with current trends in populations, projected that, some birds (such as Scottish crossbill, dotter, purple sandpiper) have a high likelihood of extinction under such an increase (Ausden *et al.*, 2015; Hayhow *et al.*, 2017). Massimino *et al.* (2017), modelling changes in climate suitability for 124 bird species in Great Britain in a scenario of approximately 4°C global warming by 2100<sup>2</sup>, showed that loss of climate suitability could lead to significant population declines for 11 species by 2080 (Figure 3.5). The largest increases are in the north and west, especially in Scotland, probably due to the expansion of more southerly species. Turnover in species abundance is higher in the west of Britain and in the south west, possibly due to the arrival of colonists (Figure 3.6).

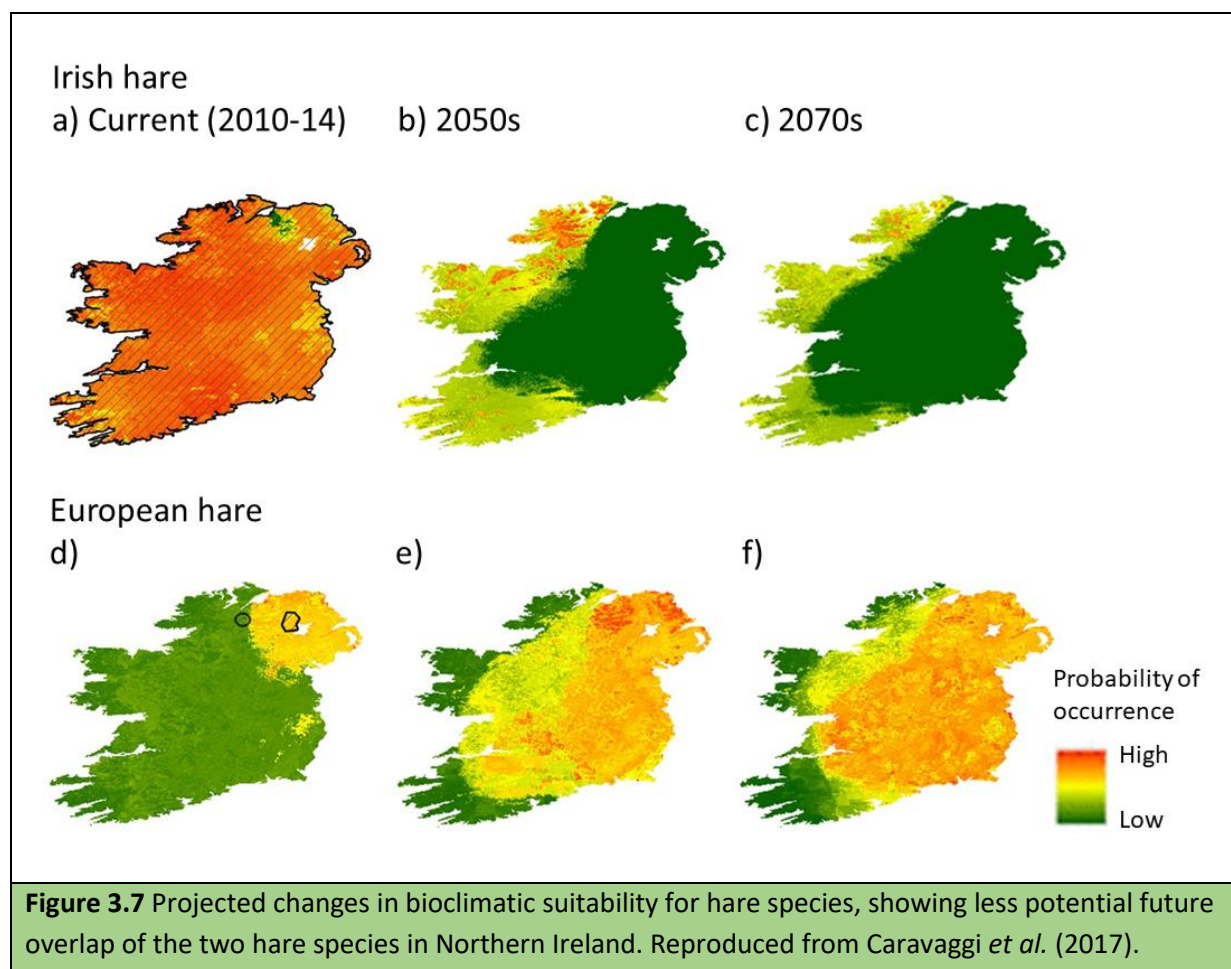
<sup>2</sup> UKCP09 spatially-coherent projections with the A1B scenario







Changes in species populations and community composition are also likely within distributional limits including as a result of the changing balance of competition between species and the impact of changing phenologies on foodwebs (Thackeray *et al.*, 2016; Donnelly *et al.*, 2018). The nature of these impacts will differ across the country according to soil type, local climate and microclimates, site management and landscape scale factors, such as the degree of fragmentation of habitats. For example, for the Scottish hare, niche overlap projections<sup>3</sup> with global mean temperature increases of 2°C for 2050 and 3.7°C for 2070 suggest that interspecific competition between European and Scottish hares could become increasingly common, leading to the latter's displacement (Caravaggi *et al.*, 2017). However, the model did not include land use change projections and given the different habitat preferences of Scottish and European hares, it is possible that the competition may be less severe and possibly mediated by habitat management to the benefit of the Scottish hare (e.g., the maintenance of heather moorland and other upland habitats). However, for the Irish hare, while the European hare may pose a short-term threat (i.e., next 30 years), in the longer-term suitable climate space for the two are less likely to overlap in Northern Ireland (Figure 3.7).



More frequent and severe extreme events may also cause local extinctions although niche shifts are an important acclimatisation or natural adaptation response in these circumstances (Roman-Palacios and Wiens, 2020). Droughts and fires are two extreme events that have been particularly

<sup>3</sup> CMIP5 climate projections with the RCP 8.5 concentrations pathway

investigated. In woodlands, future droughts could lead to crown dieback, which in severe cases could lead to tree death (see also Risk N8). High temperatures which are often associated with drought can lead to leaf stomatal closure, which can result in decreased growth, gross primary productivity and transpiration. Models have suggested that drought could lead to changes in woodland productivity, (net) carbon storage and tree composition (Berry *et al.*, 2019). The impacts of drought on managed productive woodland in Britain's forestry sector are covered in Risk N6. Greater risks are associated with repeated occurrence of events preventing recovery. Tree death and decline also has important cultural implications, for example degrading historic parkland, parks and gardens. Drought also affects grasslands and several experimental studies have shown how increasing droughts could affect other organisms, such as soil microbial communities (de Vries *et al.*, 2018) and pollinators (Phillips *et al.*, 2018) with complex effects on the whole biological community. Drought impacts on vulnerable butterfly populations appear to be influenced by the configuration of the landscape (Oliver *et al.*, 2015), with colonies less vulnerable where habitat patches had a lower ratio of edge compared to area (typically indicating a higher proportion of habitat in large blocks).

The risk of wildfire in the future is likely to increase in the UK, with about half of the increase due to rising temperatures and most of the rest to reductions in relative humidity (Arnell *et al.*, 2021). This means that south, east and central regions of England are most likely to be affected, especially in summer, with little change in western Scotland and Northern Ireland, but this partly depends on the scenario and the fire indicator. Short-term experimental evidence suggests that higher severity wildfires as a consequence of more frequent summer droughts could lead to changes in Calluna-dominated raised bog and heathland composition, with implications for ecosystem functioning and services, such as conservation and carbon storage (Grau-Andrés, *et al.*, 2019). The wildfire risk is likely to become greater with increased levels of global warming (Costa *et al.*, 2020).

There could be a reduction or loss of some tree species (e.g., beech, ash) due to pests and disease (see Risk N2), drought, and or winter waterlogging of the root zone. Hedgerows were thought to be most affected by pests and diseases, due to higher summer temperatures (Berry *et al.*, 2019). For moorland, the most significant changes are likely to be caused by hotter, drier summers altering surface water conditions and leading to changes in plant communities. Pests and diseases could also be an issue, with wetter winter conditions leading to the spread of fungi, while the higher temperatures could lead to the upward extension of the range of invasive species (e.g., rhododendron).

In assessing the risks climate change poses to National Nature Reserves in England, drawing on both scientific evidence and the practical expertise of reserve managers, Duffield *et al.* (2021) found that most of the biodiversity features (species, habitats and assemblages) for which the sites were designated were medium or high vulnerability to projected changes in the different climatic variables. The greatest levels of vulnerability were associated with projected changes in extreme events and the combined impacts of climate change. Vulnerability to changes in temperature was assessed to be lower than the other variables. There were, however, differences between habitat types, for example, wetland sites were the most vulnerable to projected changes in rainfall, whereas upland sites were the most vulnerable to temperature change.

In Wales, lowland landscapes (woodland and wetland) are likely to be affected by hotter drier summers, while the generally warmer mean temperatures could increase the effects of pests and

disease on tree cover and hedgerow species (Berry *et al.*, 2019; Risk 18). Similar factors could affect upland grassland. They suggest that upland woodlands are likely to be particularly affected by drought conditions due to hotter drier summers, which may also lead to an increased risk of wildfire. These, along with pests and diseases, may lead to some changes in the mix of tree species, including a reduction in some broadleaved species, such as oak and ash.

Coastal habitats will be affected by both climate change and sea level rise and are covered in Risk N17. Overall, the impacts are assessed as being negative, whilst recognising that on coasts where there is accretion and habitat creation there could be opportunities for habitat expansion.

### 3.2.1.3 Lock-in and thresholds (N1)

Species all have bioclimatic constraints, which are a form of natural threshold. Climate change may mean the current thresholds for suitability for some species are exceeded (as documented above). There are a very large number of different thresholds associated with terrestrial species and habitats, but often these are not documented or only become apparent in extreme conditions, such as droughts. They are also often associated with interactions between species which can be difficult to quantify. Nonetheless, the overall likelihood of threshold levels and thus potentially irreversible effects of terrestrial habitats is greater for higher levels of warming. The CCC Thresholds project (Jones *et al.*, 2020) used a critical temperature threshold of a 30-year mean temperature of 14.5°C for the warmest month and showed that by the 2080s most peatlands in the UK could be modified or highly modified. However, peatland condition is not only affected by temperature, but more often by soil moisture and management factors.

There are important lock-in risks from inaction, because once species or habitats are lost it is much harder to restore them, as not only will species need to be re-introduced, but also complex ecological functioning restored. There are also some related lock-in risks associated with protection or conservation decisions. Protected site designations and boundaries were designed before the threat of climate change was recognised and are relatively inflexible to account for changing habitats and species distributions. Moreover, some boundaries were drawn significantly tighter than guidelines recommend, notably for wetland SSSIs, omitting buffer areas that could prove important for functional resilience. Almost all protected sites are likely to remain important for conservation (Gillingham *et al.*, 2015), but may be valuable for different features other than those for which they were originally designated. The conservation objectives, indicators of favourable condition and site boundaries can all be changed in principle, but in practice doing so is a long and complex process for each of several thousand sites. Duffield *et al.* (2021) showed that Natural England's National Nature Reserves staff recognise the risk of climate change and were taking actions to build resilience, but there was less progress with accommodating change which cannot be prevented. The problem is however recognised and there are some indications that this is starting to be addressed. The UK government has commissioned the JNCC to undertake periodic reviews to ensure that the SPA network continues to support the species for which it has been designated: <https://jncc.gov.uk/our-work/special-protection-areas-overview/-spa-reviews>. In 2015, Natural England published an action plan for climate change adaptation on European protected sites (<http://publications.naturalengland.org.uk/publication/4954594591375360>), although no progress reports on this are available.

Coastal habitats and flood plains are particularly prone to change with rising sea levels (see Risk N17; section 3.21.3.4) but hold the line policies and hard sea defences are a further form of lock in, as they often prevent the coastline readjusting naturally (CCC, 2018a; Welsh Government, 2020), which may lead to the loss of habitats in front of sea defences and also catastrophic loss when sea defences fail (Haigh *et al.*, 2020).

Some land use changes, particularly afforestation, are long-term changes. Planting tree species which are not viable in a particular location in a changed climate could lock-in risk for decades into the future. Planting trees can also present long-term risks to other habitats, both in terms of direct loss or fragmentation and indirectly by preventing the creation of larger blocks of habitat or changing the hydrology of catchments. For example, the Natural Capital Committee (2020) suggest that appropriate spatial planning is needed when tree planting in order to avoid the possible loss of other habitats and land uses, such as species rich grasslands, heathlands and peatlands, especially if they are degraded.

#### 3.2.1.4 Cross-cutting risks and interdependencies (N1)

These include:

- New / increased invasive species and pathogens encouraged by climate change (Risk N2) exacerbating the direct effects on terrestrial habitats and species.
- Abstraction of water exacerbates drought effects by reducing water to support ecosystems.
- Drainage of wetlands has reduced water holding capacity, increasing the risks of drought.
- Canalisation of water courses increases flow rate and reduces water holding capacity of catchments. Similarly, drainage of wetlands has reduced water holding capacity.
- New evidence since CCRA2 on the interactions between land use and climate change, areas with more semi-natural habitat and less fragmentation of habitat show more resilience to climate change and extreme events (Oliver *et al.*, 2015; Watts *et al.*, 2020).
- Flood responses - hard coastal and riverine defences preventing roll back and natural river function, while natural flood management could restore wetlands and improve the conditions of habitats.
- Following drought there may be increased concentration of fertilisers, pesticides and other chemicals, but the peak concentration might happen after the rains return and flow is restored. The drought conditions themselves are unlikely to result in increased concentrations of fertilisers.
- Drought, combined with increased access and engagement could lead to increased risk of wildfire, especially on heathland and grasslands.

#### 3.2.1.5 Implications of Net Zero (N1)

The Net Zero target has the potential to both increase or decrease climate change risks to the natural environment. Changes in land use and management will need to be an integral element of delivering the UK Government's target of Net Zero greenhouse gas emissions by 2050. The specific target differs between the nations, England's is 100% reduction by 2050, while the Welsh Government has also set a Net Zero target for 2050 and the Scottish Government has a commitment

to a target of net-zero emissions of all greenhouse gases by 2045. One commonly advocated climate change mitigation measure is an increasing use of biofuels, including bioenergy with carbon capture and storage (BECCS). Given evidence that intensive management of agricultural land had the biggest impact on plant, insect and vertebrate populations (Burns *et al.*, 2016), an emphasis on productivity of biomass for Net Zero could lead to negative effects. Edible crops (maize, corn) for bioenergy can compete with land for biodiversity and for food crops, (see Risk N6), while an increase in the planting of short rotation forests or coppice can present a threat of habitat loss, although if sited well and carefully implemented this can be reduced.

In order to free up agricultural land for other uses the productivity of remaining agricultural land will need to increase together with a reduction in food waste and the consumption of meat and dairy products associated with high emissions (CCC, 2019a). An intensification of agricultural production could lead to a loss of biodiversity and increased vulnerability to climate change. In Wales, the main developments that will be able to address Net Zero are the new Sustainable Land Management Scheme and National Forest and Peatland Restoration Programme, which will all provide a combination of mitigation benefits linked to Net Zero along with enhancing ecological resilience alongside local/regional green infrastructure initiatives.

Peatland restoration is an opportunity for mitigation and adaptation co-benefits. Many peatlands in the UK have been degraded by drainage, burning, afforestation and conversion to agricultural land leading to high rates of CO<sub>2</sub> emissions (Evans *et al.*, 2017). Even where semi-natural vegetation continues on drained peatland its character is changed, for example with the loss of Sphagnum species. Also, there is an increased risk of wildfire during periods of drought, which can lead to significant carbon loss. Restoration of peatlands, by blocking drainage, removing trees and stopping burning, can reduce and in time prevent emissions at the same time as recovering the biodiversity. Re-wetting peatlands would be expected to improve resilience to droughts, both within the habitat itself and potentially within the wider catchment; it would also be expected to reduce wildfire risk.

Woodland creation and tree planting can be beneficial for biodiversity and adaptation if carried out appropriately. Biodiversity benefits are greater with native species, which are all broadleaves, with the exception of Scots Pine in Scotland. Some tree species and provenances will be better suited to our future climate; this includes a number of native species, such as hornbeam and small leaved lime. A naturally regenerating woodland, rather than a planted one can also maximise genetic variation which increases chances of some individual trees surviving. The concept of nature-based solutions has become increasingly prominent in thinking on climate change adaptation and mitigation. A true nature-based solution addresses societal challenges, such as climate change, with benefits for both people and biodiversity (IUCN, 2016, 2020). For adaptation, planting trees in the right place in a catchment or allowing them to regenerate naturally can contribute to Natural Flood Management (EA, 2018a). Allowing trees and branches to fall and remain on the ground can enhance this effect by creating woody debris dams that slow the flow of flood water. Improving infiltration of water into the soil and reducing the rate at which water drains from catchments, may also help to reduce the impacts of drought events, although there is no evidence to demonstrate this at present.

There is a risk to biodiversity from afforestation if this leads to large scale planting of non-native species or if trees are planted on existing semi-natural habitats; if they are planted on peatlands

(which is limited under the UK Forestry Standard, but still allowed on shallow peat soils) this can lead to emissions of greenhouse gases. Water demanding species also present the risk of reducing water supply in catchments during drought periods. Planting tree species which are not adapted to a changing climate could lead to poor growth rates and increased risk of mortality, particularly during drought events. There are also risks from increased from new pests and diseases (Risk N2; Risk N8). Monocultures of species are more at risk than a diversity of species – a diverse stand reduces the risks of all trees dying or declining. This has implications not just from the perspective of timber yield and carbon, but for biodiversity, as different species of tree support different species of epiphytes, invertebrates and ground flora. Ash dieback, although not caused by climate change, both illustrates the risks and exacerbates the risk of further loss of species; in making decisions about replacing ash in woodlands (Broom and Mitchell, 2017) it will be important to consider the climate change implications.

There is an overarching risk that, because reducing emissions or promoting sequestration is a conceptually simpler problem than adaptation to climate change, decisions will be taken which promote carbon uptake at the expense of adaptation. It is, therefore, important that the impacts of actions deployed to further Net Zero objectives also are evaluated for their impacts on biodiversity and adaptation (Morecroft *et al.*, 2019), as there is potential for adverse effects (both direct and indirect) of afforestation on habitats, for example some wetlands, species-rich grasslands and habitats with organic soils (including shallow peat).

#### 3.2.1.6 Inequalities (N1)

No inequalities associated with climate change were identified in relation to risks and opportunities from terrestrial species and habitats. See Risk N2 for inequalities related to risks from pest, pathogens and Invasive non-native species (INNS).

## 3.2.1.7 Magnitude Scores (N1)

<b>Table 3.2</b> Magnitude scores for risks to terrestrial species and habitats from changing climatic conditions and extreme events, including temperature change, water scarcity, wildfire, flooding, wind, and altered hydrology (including water scarcity, flooding and saline intrusion).					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (medium confidence)	High  (Medium confidence)
<b>Northern Ireland</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Scotland</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Wales</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)

Notes: Magnitude categories based on the level of agreement of the evidence and expert judgement of authors (in agreement with CCRA reviewers) of high present day and therefore likely high magnitude impacts on species groups across all four UK countries (category: 'Major impacts on or loss of species groups'). Also, in the context of pollinators, the magnitude is classed as high for all UK countries; 'category: Major impact (10% or more at national level) to an individual natural capital asset and associated goods and services.

### 3.2.2 Extent to which current adaptation will manage the risk (N1)

#### 3.2.2.1 Effects of current adaptation policy and commitments on current and future risks (N1)

##### 3.2.2.1.1 UK-wide

Many generic actions for nature recovery, such as creating bigger, better, more and more connected areas of semi-natural habitats (Lawton Review, 2010), contribute to adaptation in that they build the resilience of ecosystems and can enable species to respond better to climate change. These ‘Lawton’ principles’ have been widely recognised priorities for nature conservation over the past ten years and are starting to influence planning of ecological networks of sites (Crick *et al.*, 2020). To build resilience of ecosystems to climate change this will need to go much further. However, the evidence is also clear that the Lawton principles will not be sufficient in themselves and targeted adaptation actions are needed to tackle specific risks to species and habitats. Statutory and planning processes of conservation also need to change to take account of those inevitable changes in species distributions and habitat features, which we cannot prevent under any adaptation scenario. The significance of climate change risk for the assessment of natural capital (Dasgupta *et al.*, 2021) and the opportunities arising from a natural capital approach also need to be considered in much greater depth.

A number of generic adaptation measures, some of which overlap with general nature recovery, have been recognised for increasing the resilience of biodiversity to climate change (Morecroft *et al.*, 2012; Prober *et al.*, 2019; Natural England and RSPB, 2020). These include: reducing other pressures on biodiversity (Gillingham *et al.*, 2015; Oliver *et al.*, 2017), including agricultural intensification, habitat fragmentation and potentially INNS; increasing the number and size of protected sites (Pavón-Jordán *et al.*, 2020; Eigenbrod *et al.*, 2015; Oliver *et al.*, 2015), as well as providing buffer areas around them; improving the functional connectivity between sites (Keeley *et al.*, 2021); maintaining or increasing habitat heterogeneity; protecting or creating cool microclimates and potential refugia for species (Suggitt *et al.*, 2018) and species translocations (e.g., National Species Reintroduction Forum, 2014; Brooker *et al.*, 2018). An assessment of the drivers of population changes (1970–2012) for 322 species found, conservation measures that might be undertaken as part of climate change adaptation, especially low-intensity management of agricultural land and habitat creation had the most positive impact on insect, plant and vertebrate species (Burns *et al.*, 2016). There is now a reliable evidence base for developing and implementing adaptation plans nevertheless it is important to test the effectiveness of adaptation measures through long-term monitoring, as they take time to achieve their objectives (Morecroft *et al.*, 2019) and this in turn can help to improve adaptation.

The CCRA2 Evidence Report noted that the national adaptation programmes and strategies of all four UK nations recognise the need for adaptation and the need to build ecological resilience (see below). It also stated that increasingly changes will be needed to approaches to conservation management at the site level. Ambitious policy aspirations have been set across all four UK nations to halt long-term declines in biodiversity and improve the condition and coherence of ecological networks (e.g., DAERA, 2019a; Defra, 2018a; Scottish Government 2019; Welsh Government, 2019b). Meeting these targets would do much to improve the resilience of habitats and species to



current and future climate change, and to safeguard the provision of vital ecosystem goods and services. Delivering these commitments on species and habitats and implementing them in a way that plans for climate change adaptation is critical to protecting species and habitats going forward and will require significant investment. This has yet to be committed and past targets have often not been met (for example under Biodiversity 2020 in England; Hawkins *et al.*, 2019). The statutory conservation agencies have produced a large amount of evidence and high-quality advice documents to enable practitioners to adapt to climate change at local scales (see below). This was an important step, but there is a long way to go in delivering adaptation on the ground (Duffield *et al.*, 2021).

Some change in species and habitats is inevitable, for example, in species distributions and the composition of biological communities, even with much more ambitious resilience building and adaptation measures. This will mean that many existing conservation plans for sites and species and the designations of protected areas becoming out of date (Duffield *et al.*, 2021). There are examples of nature reserve management plans being reviewed and adjusted to take account of this in some cases, for example, Natural England and RSPB both have programmes to do this (Natural England and RSPB, 2020). However, this is not happening across most protected areas including Sites of Special Scientific Interest, although there are examples of change at coastal sites where terrestrial habitats are changing into coastal habitats as a result of natural processes or managed realignment. The statutory conservation agencies have produced a large amount of evidence and advice documents to facilitate climate change management (see below).

- i. Elements of all of the national adaptation programmes and strategies support particular generic adaptation measures. Examples for each UK nation are given below related to the following adaptation strategies: Increasing the number and size of protected sites - protected areas (Sites of Special Scientific Interest) have been found to be effective for the species persistence of a selection of birds and butterflies in Great Britain, especially at trailing-edge warm range margins at lower altitudes and latitudes and for species expanding their range margins (Gillingham *et al.*, 2015).
- ii. Habitat restoration – this often involves reducing pressures from other sources and restoring natural ecosystem process. For example, there are a number of relevant schemes for peatland restoration (see Risks N4 and N5) as part of or in addition to the UK Peatland Strategy. It should be noted that climate change shifts the balance of what sort of restoration is important e.g., hydrological restoration will be more important with more droughts and floods.
- iii. Habitat creation - each UK country has targets for tree planting and woodland creation, partly driven by strategies for achieving Net Zero. However, if they are sited and implemented in the right way (ensuring that species planted and management decisions take climate change into account), these activities could help support adaptation, as well as climate mitigation.
- iv. Ecological connectivity – ecological connectivity can be assisted through establishing ecological networks (Crick *et al.*, 2020) and it is supported by policies in all four UK nations.
- v. Translocation/assisted colonisation. This is becoming a more common adaptation response and is starting to appear in policy documents (e.g., see Scottish Government example below).

It should be noted that this does not include some specific adaptation actions, such as the protection of refugia or adjustment of management to take account of changing conditions. Maintaining or restoring cultural landscapes (N18; Chapter 5, H11: Kovats and Brisley, 2021) and traditional land management practices has been an important element of conservation to date. This may be helpful in terms of building resilience of species and habitats associated with these areas, however in some cases traditional practices may need to adapt to changing conditions – for example hay cut may need to take place earlier in the summer.

Each country also has a pollinator plan focused on reducing their loss, summarised below.

### 3.2.2.1.2 England

The 25 Year Environment Plan has a commitment to establish a Nature Recovery Network, which will address ambitious goals including restoring goals both to restore 75% of terrestrial protected sites to favourable condition and to create or restore 500,000 hectares of additional wildlife-rich habitat outside of protected sites. This, if implemented, will contribute to ecological connectivity (linking to both i) and iv) above). Defra is developing an 'England Peat Strategy', linked to the 25-Year Environment Plan, with a vision that all peatlands should be managed sustainably within 25 years. Pollination is included as an important ecosystem regulating function within 25 Year Environment Plan (25YEP) indicators framework under Thriving Plants and Wildlife (D7) and currently is using trends in the distribution of UK pollinators as an interim indicator. The currently delayed Environment Bill contains a number of proposed measures to support nature's recovery in line with the ambition set out in the 25 Year Environment Plan.

At the moment the key delivery mechanism for the aspirations in the 25 Year Environment Plan is the Countryside Stewardship Scheme. This will be replaced by the Environmental Land Management Scheme in 2024, which will also re-direct funding which has to date been allocated to the Single Farm payment, following the model of the EU Common Agricultural Policy. Whether this will deliver the objectives of 25 Year Environment Plan and whether climate change will be adequately addressed is not possible to judge at this stage. This will be a key challenge for the next 5 years – with sufficient funding and full integration of climate change adaptation it could make a transformatory difference, including for landscape scale restoration and rewilding.

A number of other funding channels are available. A key one is the £640m Nature for Climate Fund which will support a range of actions to assist nature-based solutions for climate change mitigation, with a focus on woodland creation and peatland restoration. This also has great potential to support biodiversity and climate change adaptation, particularly if a significant element of native woodland is included and adaptation principles are built into all projects.

An updated adaptation manual for England has been published that embraces the above measures and to support conservation managers in adapting to climate change (Natural England and RSPB, 2020). In addition to enhancing ecological resilience, it recognises the need to prepare for and accommodate inevitable change; valuing the wider adaptation benefits the natural environment can deliver and improve the evidence base.

The Forestry Commission Woodland Indicator includes connectivity as a measure of the size and distribution of patches of forests and woodlands, relative to a value of 100 assigned to 2011. The indicator shows an increase in connectivity for forests and woodlands in England between 2010 and 2017. Over the same period there has been a corresponding increase in the area of forests and woodlands. The change in connectivity may be related to the overall increase in the woodland resource, the location in which new woodlands have been planted (i.e., in relation to existing woodland), or both. Much of the new planting that has occurred has been funded through agri-environment schemes, such as Countryside Stewardship, which encourages applicants to consider connectivity in their plans. The maintenance or restoration of linear features in heritage landscapes (Risk N18) could also contribute to enhancing connectivity.

England's National Pollinator Strategy vision is to see pollinators thrive, so they can carry out their essential service to people of pollinating flowers and crops, while providing other benefits for our native plants, the wider environment, food production and overall human welfare. The Implementation Plan for 2018-2021 considers that success will include: improvements in the condition of protected sites; increases in the extent, quality or connectivity of wildflower-rich habitat outside protected sites and continued uptake of pollinator-friendly agri-environment packages (Defra, 2018b).

#### 3.2.2.1.3 Northern Ireland

Northern Ireland is also restoring its peatlands and other ecosystems, such as ancient woodlands (Climate Northern Ireland, 2019). The All-Ireland Pollinator Plan 2015-2020 (National Biodiversity Data Centre, 2015), which is for the island of Ireland, including Northern Ireland, recognises that pollinators are vulnerable to climate change, but that its impacts on them are difficult to predict. Increasing the connectivity and quality of pollinator friendly habitats are suggested for enabling the movement of pollinators in response to climate change.

#### 3.2.2.1.4 Scotland

Ecological connectivity is part of the monitoring framework to ensure that the natural environment is protected and enhanced (Scottish Government, 2019).

The Scottish Code for Conservation Translocations, for example, has been published to promote the use of best practice (National Species Reintroduction Forum, 2014). An NSIF project led by NatureScot and Royal Botanic Garden Edinburgh is working to identify species for which assisted colonisation and other types of conservation translocation may provide significant benefits. In Scotland, some experimental translocations for threatened alpine species have taken place and have provided evidence on best practice (Scottish Government, 2019). While in Creag Meagaidh National Nature Reserve the feasibility of moving some individuals of the lichen, *Flavocetraria nivalis*, from the high Cairngorms into Creag Meagaidh (which is outside the species' climatic range) is being explored, as a form of assisted colonisation.

The National Peatland Plan aims to support an increase in the annual rate of peatland restoration, from 10,000 hectares in 2017-2018 to 20,000 hectares per year thereafter (SNH, 2015) Also,

Scotland's Peatland ACTION programme has seen significant increases in investment from £3M in 2018/19 to £14M in 2019/20.

The Pollinator Strategy for Scotland 2017-2027 (NatureScot, 2017) sets out how Scotland can continue to be a place where pollinators thrive, along with actions that are needed to help achieve that objective.

#### 3.2.2.1.5 Wales

The Welsh Government has established an adaptive natural resource management framework following from the Environment (Wales) Act which includes establishing resilient ecological networks. A National Peatland Restoration Programme has been published (Natural Resources Wales, 2020), targeting peatland bodies most in need of restoration with the aim of delivering 600-800 hectares of restoration per year. There have been a range of large-scale habitat restoration projects (often EU funded) that are addressing upland peatland e.g., upper Conwy catchment, lowland mires e.g., Sands of Life project which will restore over 2400 ha of sand dunes across four Special Areas of Conservation, on 10 separate sites, as well as compensatory saltmarsh creation through the National Habitat Creation Project. In the Welsh Adaptation Plan under 'Adaptive Nature', there is an action to develop functional resilient ecological networks, with a database to be combined with ecosystem service assessment (Welsh Government, 2019b).

The Wales Action Plan for Pollinators (2013) sets the strategic vision, outcomes and areas for action to improve conditions for pollinators and work to halt and reverse their decline in Wales. A review of the plan was published in 2018 (Welsh Government, 2018b) and adds additional actions. Although the original plan did not include a specific action around climate change, the review document does detail where the action plan has been of benefit to adaptation for pollinators and sets out future actions such as Pennal 2050. The plan also sets out actions to reduce pressures on pollinators from other sources (land-use intensification, habitat destruction and fragmentation, disease, the use of agro-chemicals). The need to protect and improve conditions for pollinators is recognised in Natural Resources Wales' Area Statements for Wales, an important part of Wales' Natural Resources Policy. Part 2 of the Wales Nature Recovery Plan has also been refreshed for 2020-2021 to address issues driving the decline in biodiversity, including climate change.

The role of flood risk management and water quality for supporting terrestrial habitats and species is also recognised under the National Strategy for Flood and Coastal Erosion Risk Management in Wales (Welsh Government, 2020), setting out many actions to build flood resilience in otherwise impacted habitats. Water Resource Management Plans and River Basin Management Plans also provide policy in Wales for habitat protection from a water resource perspective.

#### 3.2.2.1.6 Impacts of EU-Exit and Covid-19

At the present time the policy and legal framework for support of biodiversity is changing, largely driven by the UK's exit from the European Union. The details of the new policies and legislation that are being developed have not been finalised, so it is not possible to assess their likely effectiveness in helping address adaptation. The level of funding for sustainable land management and the rules

concerning how it is spent will also be critical to how much is achieved and thus there is a risk of insufficient government funding to enable nature recovery. In our view there could also be a risk that EU-exit could lead to the lowering of environmental protection standards to enable trade deals with other countries.

Covid-19 has led to, at least, a short-term loss of income for NGOs, leading to decreased conservation action from them. However, the £40 million Green Recovery Challenge Fund might help, although it is probably not sufficient for the level of nature recovery needed. Biodiversity is viewed as part of a green recovery, helping to address risks to society and the economy, but needing a number of actions including the scaling up of investment in biodiversity conservation, its sustainable use and restoration (OECD, 2020). This report also recognises that the challenges of addressing climate change and biodiversity loss are closely related.

Covid-19 has led to more people spending time outdoors, possibly resulting in greater environmental engagement, as well as the realisation of the importance of the natural environment, especially to human health and well-being. Although at the same time, there has been large scale reporting in the media of damage to landscapes from increased litter and footfall (e.g., <https://www.bbc.co.uk/news/uk-england-cumbria-53693300>). While at some sites there is a suggestion that the lack of human disturbance has led to improvements in biodiversity (e.g., <http://www.msn.com/en-gb/news/uknews/endangered-species-of-seahorse-returns-to-former-stronghold-due-to-lockdown/ar-BB14URMj?ocid=ientp>).

### 3.2.2.2 Effects of non-Government adaptation (N1)

Acclimatisation and natural adaptation will take place (as discussed above), but our view is that this is insufficient to address the adaptation gap. Some of this shortfall will be addressed by non-Governmental stakeholders, as many are undertaking adaptation relevant actions. There are a considerable number of projects undertaken by the RSPB, National Trust, Woodland Trust and DA Wildlife Trusts (e.g., Living Landscapes and Futurescapes). These are delivering improved habitat management or restoration that will enhance resilience. For example, the National Trust is involved with a range of projects for the research, restoration and management of peatlands in England and Wales and is intending to restore or create 3,269 hectares of peatland habitat, of which 2,070 hectares is underway and 665 hectares is complete. While in Northern Ireland, under the INTERREG funded Collaborative Action for the Natura Network, Ulster Wildlife have been re-wetting over 1000 ha of peatland.

There are also a number of other initiatives, such as rewilding, which may involve private landowners. This involves a more ecosystem approach to the restoration of habitats and natural processes, as well as often trying to address issues of connectivity to facilitate reactive adaptation.

### 3.2.2.3 Barriers preventing adaptation (N1)

There are a number of barriers and constraints to adaptation (relevant to all risks in this chapter), which make it difficult for organisations (public and private) to plan and implement adaptation actions (Cimato and Mullan, 2010; HMG, 2013). These various barriers can make it difficult to make

decisions or take action, even when it is clear that action is needed. They include uncertainty, which translates through to the market failure of imperfect information. Further, many adaptation actions – especially for the natural environment – have a public goods or non-market dimension in which the private sector is unlikely to invest. The available resources to adapt is often an issue. There are also policy, institutional and governance barriers to adaptation, which may make it harder for Government to implement adaptation, or to create the enabling environment for the private sector or individuals to adapt.

Currently, our view is that the policy framework is in place with appropriate conservation objectives but lacks coherent delivery of widespread landscape-scale adaptation that not only builds ecologically resilient networks, but also ensures that wider environmental benefits are achieved. This is likely due to a combination of the barriers above.

Resources, in particular limited conservation budgets, are also a constraint on implementing adaptation actions, so other, innovative, sources of funding need to be found. There are an increasing number of options and one option could involve conservation organisations developing finance-ready proposals for investment in biodiversity through green finance (RSPB, 2018).

Land availability for habitat creation and networks can also be a constraint as there are many competing demands on land to provide food, timber, bioenergy, recreation etc. However, agri-environment schemes could increase the engagement of landowners in conservation activities and enhance species resilience and adaptation potential for climate change e.g., restoring/creating new habitats, such as hedges. While Net Zero offers the potential to increase resilience and build climate change adaptation into land management, it is essential to ensure that species and habitat priorities are accommodated, perhaps by using a more systemic nature-based solutions approach to achieving Net Zero in land use and agriculture.

#### 3.2.2.4 Adaptation shortfall (N1)

Plans are in place in all the UK nations (see above) that contain targets, which if met, would make significant steps in halting and reversing decades of degradation and fragmentation of the natural environment in the UK and thereby facilitating adaptation. However, at the time of writing it is not clear that the various aspirations in the plans are on track to be met. Current plans and targets could benefit from a more specific set of actions for climate change beyond habitat condition, which could include more on planned site alteration to address climate threats (drought, flood, wildfire), spatial planning at small scale (allowing species to move) and large-scale networks. Funding schemes to replace the Common Agricultural Policy (CAP) post EU-Exit also need to take steps to ensure that actions to reduce vulnerability and exposure to climate change are rewarded. As climate change continues, a commitment to review regularly and if necessary, adjust the boundaries and/or the conservation objectives of protected sites, species objectives and the indicators of favourable condition would facilitate adaptive management. As such, our view is that the risk is being partially met across the UK (Table 3.3), but further action would help to meet the adaptation shortfall by ensuring targets are on course to be met, and putting in place further policies for land management that support adaptation post EU-Exit.

## 3.2.2.5 Adaptation Scores (N1)

<b>Table 3.3</b> Adaptation scores for risks to terrestrial species and habitats from changing climatic conditions and extreme events, including temperature change, water scarcity, wildfire, flooding, wind, and altered hydrology (including water scarcity, flooding and saline intrusion)			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Medium to low confidence)	Partially (Medium to low confidence)	Partially (Medium to low confidence)	Partially (Medium to low confidence)

## 3.2.3 Benefits of further adaptation action in the next five years (N1)

The CCRA2 Evidence Report concluded that further action is needed now and into the future to increase current efforts to reduce existing pressures, improve the ecological condition of protected wildlife sites, and restore degraded ecosystems, such as peatlands, wetlands and native woodlands. There is a window of opportunity to build the resilience of habitats, through a range of measures that will improve the capacity of species and biological communities to persist and adapt. This is important as once species or habitats are lost it is much harder to restore them, as not only will species need to be re-introduced, but also complex ecological functioning restored, if that is even possible. Ecological restoration can take many decades for some habitats, meaning that there are long lead-in times for adaptation action. This has not changed and there is a need to take more flexible and integrated approaches to managing natural capital, including further realignment of the coast, catchment-scale management strategies, and landscape- scale initiatives to increase habitat extent and improve habitat condition and connectivity.

Climate and environmental change, therefore, should also be more explicitly accounted for in conservation planning at the site level and more widely. This may include modifying conservation objectives and planning for and anticipating necessary changes in spatial distribution, for example by identifying and securing refugia. Site level conservation objectives and plans would benefit from being reviewed to assess whether management is appropriate for new or potential colonists and adapted accordingly. It is important that planning begins in time for action to be effective.

Increasingly the link is being made between climate change and biodiversity loss, with nature-based solutions being an important way of addressing these two together (see Box 3.3; Section 3.21.2). Nature-based solutions will help deliver adaptation actions including: developing resilient ecological networks; increased canopy cover and well-located woodland for greater habitat availability and ecosystem service value; maintaining, enhancing and restoring floodplains and hydrogeological systems to reduce flood risk and improve water quality and quantity; restoration of uplands and managing them for multiple benefits.

### 3.2.3.1 Indicative costs and benefits of additional adaptation (N1)

The valuation of the impacts of climate change on terrestrial species and habitats is challenging, and this makes it difficult to analyse the subsequent benefits of adaptation in reducing these risks. It is also highlighted that while the literature on the costs and benefits of adaptation is improving, there is very little information on the costs and benefits of helping natural systems adapt (Tröltzsch *et al.*, 2018). There has been some analysis on the costs and benefits of peatland restoration (Moxey and Moran, 2014; Bright, 2019, Watkiss *et al.*, 2019), which indicate that restoration is generally worthwhile in most (but not all) cases, for both upland and lowland peatlands (i.e., with positive benefit cost ratios). The benefits increase if more ecosystem services are able to be valued (and this is a general issue for many risks in this chapter) and climate change strengthens the case for restoration. There are some case studies on cost-effectiveness or cost benefit analysis of buffer zones, migration corridors and even translocation for specific habitats or species (e.g., Tainio *et al.*, 2014) though this remains a gap (especially on the benefits analysis). Finally, there would seem to be a strong economic case for an expanded role for Government intervention to provide enhanced monitoring and surveillance and early response.

### 3.2.3.2 Overall urgency scores (N1)

**Table 3.4** Urgency scores for risks to terrestrial species and habitats from changing climatic conditions and extreme events, including temperature change, water scarcity, wildfire, flooding, wind, and altered hydrology (including water scarcity, flooding and saline intrusion).

Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	More action needed	More action needed	More action needed
Confidence	Medium	Medium	Medium	Medium

There is much evidence of the current and potential risks of climate change to terrestrial ecosystems as set out above and while there are extensive current and planned adaptation measures there is a gap in understanding how aspirational targets that are set out in policy are planned to be met through actions, as well as a continuing lack of evidence on how actions are reducing vulnerability and exposure. A potential trade-off that also needs to be considered is the potential risks from mitigation options for Net Zero that are implemented without sufficient regard for maintaining or enhancing biodiversity in its adaptation to climate change.

Thus, the risk remains High and more action is needed.

### 3.2.4 Looking ahead (N1)

Given the state of flux around many policies following EU-Exit, decisions made in the next few years could have a profound effect on the natural environment for decades to come. Much of the UK's natural environment is degraded with many species at risk and successful adaptation will not be



possible without a significant investment in restoring natural areas. Equally, investment in nature recovery will be at risk if climate change adaptation is not fully embedded into planning from the start. It is essential that adaptation is consistently factored into decision-making alongside climate change mitigation and the protection of biodiversity from the start. It will also be essential to embed the concept of nature-based solutions at the heart of climate change adaptation across other sectors, including agriculture, flood risk management, water supply, infrastructure and urban planning. The opportunities for co-benefits are high but there are also serious costs if this does not take place. There are good indications that these issues have been recognised in policy development, but as yet the mechanisms for delivery are unclear and the level of funding undetermined: the risks to people and nature are serious and the cost of addressing them should not be underestimated.

There is limited evidence on the effectiveness of adaptation actions in this area and it is intrinsically difficult to assess the extent to which harm has been avoided, especially given the long timescales over which both climate change and ecological processes operate. Consistent, long-term monitoring and assessment will be important to inform adaptive management and build a robust evidence base for further action.

### 3.3 Risks to terrestrial species and habitats from pests and pathogens, including Invasive Non-Native Species (N2)

- Despite strong international and national policy frameworks for managing the risks to terrestrial species and habitats from pests and pathogens, these risks are expected to continue increasing. Support for INNS is generally less well developed and resourced than for other pests and pathogens.
- Current risk assessment and management measures provide some adaptive capacity to reduce these risks, but there is a compelling need for enhanced monitoring, surveillance and early response measures to prevent a spread.
- The magnitude of current and future risks is assessed as medium, but high for future risks in England, based on the combination of its closer proximity to continental Europe and generally higher temperatures which result in a higher likelihood of incursions of some INNS prevalent in Europe and their establishment in warmer areas of England. The magnitude score is high for all countries in the 2080s under a 4°C world.
- These risk levels could change with improved understanding of the specific climate responses and thresholds of high-risk pests and pathogens, and the potential change in risk associated with adaptation options.

#### Introduction

The introduction, establishment and spread of pests and pathogens, including Invasive Non-Native Species (INNS), and the risks they pose to terrestrial species and habitats involves complex interactions between biotic and abiotic factors. Changes in these risks are primarily influenced by socioeconomic drivers, including cross-border trade, within-country movements, biosecurity measures and land use change. Climate variability and change is generally considered a second order

influence on these risks through its impact on the life cycle and spread of pests and pathogens, or incursion and establishment of INNS. In recent years, warmer winters have had a clear influence on outbreaks and incursions of some pests and pathogens in the UK. UKCP18 climate projections show continued warming and changing patterns of extreme events across the UK, which is expected to expand the range of climate suitability for many pest and pathogen species and increase the chance of establishment of INNS, thereby increasing the future risk to terrestrial species and habitats.

### 3.3.1. Current and future level of risk (N2)

Note: currently available evidence is not sufficient to allow us to report on the current and future level of risk for each UK country separately.

#### 3.3.1.1 Current risk (N2)

Pests, pathogens and INNS have the potential to disrupt key ecosystem functions and cause significant economic damage. They threaten individual species or whole habitats and can severely impact a range of ecosystem services, e.g., carbon storage and biodiversity, and cultural heritage, e.g., parks, gardens and designed landscapes. Evidence of recent increases in the number and severity of outbreaks of native pest and pathogen species, and establishment of INNS, indicate that risks to terrestrial species and habitats have continued to increase since CCRA2. Increasing international trade, especially in high-risk products such as horticultural plants and wood packaging, has been a primary driver for the rise in INNS introductions. For example, in July 2019, 60 sites across UK were exposed to oak processionary moth (*Thaumetopoea processionea*) caterpillars imported with oak trees from the Netherlands and Germany (<https://www.forestresearch.gov.uk/tools-and-resources/pest-and-disease-resources/oak-processionary-moth-thaumetopoea-processionea/>). Low probability high impact events, such as multiple high-risk pest or pathogen outbreaks in close succession across the UK, could cause major agricultural losses and disruption, from which it would be challenging to recover.

Recent warmer winters across the UK have favoured the survival and development of many pests and pathogens, and incursion and establishment of INNS. For example, in July 2019, an outbreak assessment by the Animal and Plant Health Agency (APHA) on the bluetongue virus serotype 8 strain (BTV-8) noted that warm conditions in the UK and northern Europe at that time were favourable for both adult *Culicoides* midge activity and bluetongue virus replication within the midge vectors (Defra, 2019b). Native UK tree species are particularly at risk. For example, from its first discovery in the wider UK environment in October 2012, the spread of ash dieback disease by the *Hymenoscyphus fraxineus* fungus continued rapidly, covering 61% of the UK landmass by 14<sup>th</sup> May 2020 (<https://www.forestresearch.gov.uk/tools-and-resources/pest-and-disease-resources/ash-dieback-hymenoscyphus-fraxineus/>). In Scotland, two of the most significant risks to forest resources and woodland biodiversity come from *Phytophthora ramorum*, a fungus-like pathogen that is a particular threat to larch, and *Dothistroma* needle blight (DNB), which poses a particular threat to Scotland's commercial forestry and also to native Caledonian pinewoods. Although the causes of recent increases in DNB are currently unclear, some evidence suggests that increased rainfall in spring and summer coupled with warmer springs have optimised conditions for spore dispersal and infection (Brown and Webber, 2008). The juniper disease, *Phytophthora austrocedri*, first confirmed

in the UK in 2011, has also spread rapidly to sites across northern England and Scotland (<https://www.forestresearch.gov.uk/tools-and-resources/pest-and-disease-resources/phythophthora-austrocedri/>). On the island of Ireland, ash dieback was first identified in October 2012 and had been detected at 306 sites (195 in Republic of Ireland and 111 in Northern Ireland) by 2017 (McCracken *et al.*, 2017). The vast majority of outbreaks were on young, imported trees, although it was also noted that the pathogen cycled within a plantation or moved to infect neighbouring hedgerow trees. A study of hedgerow trees in Northern Ireland highlighted the general poor condition of many hedgerow trees, especially ash due to canker, threatening the ecosystem services provided by hedgerow standard trees (Spaans *et al.*, 2018). Also, a study of the declining health of alder trees along the river Lagen in Belfast noted serious disease from various *Phytophthora* species, including the first report of *Phytophthora lacustris* in Northern Ireland (O'Hanlon *et al.*, 2019). Other important diseases threatening woodland ecosystems in general are *Phytophthora alni* and oak decline (<https://www.forestresearch.gov.uk/tools-and-resources/pest-and-disease-resources/>). A detailed review of forest and woodland pests, pathogens and diseases is available in Section 3.10.

Invasive non-native (plant and predator) species can create risks and opportunities for pollinator nutrition and reorganise species interactions to affect native pollination and community stability (Vanbergen *et al.*, 2018). Currently there are comparatively few recorded accounts of alien plant invasions in the UK consistently lowering pollinator diversity or abundance (Steele *et al.*, 2019), but there are a large number of knowledge gaps and it is not clear what role climate change has had in their arrival or spread.

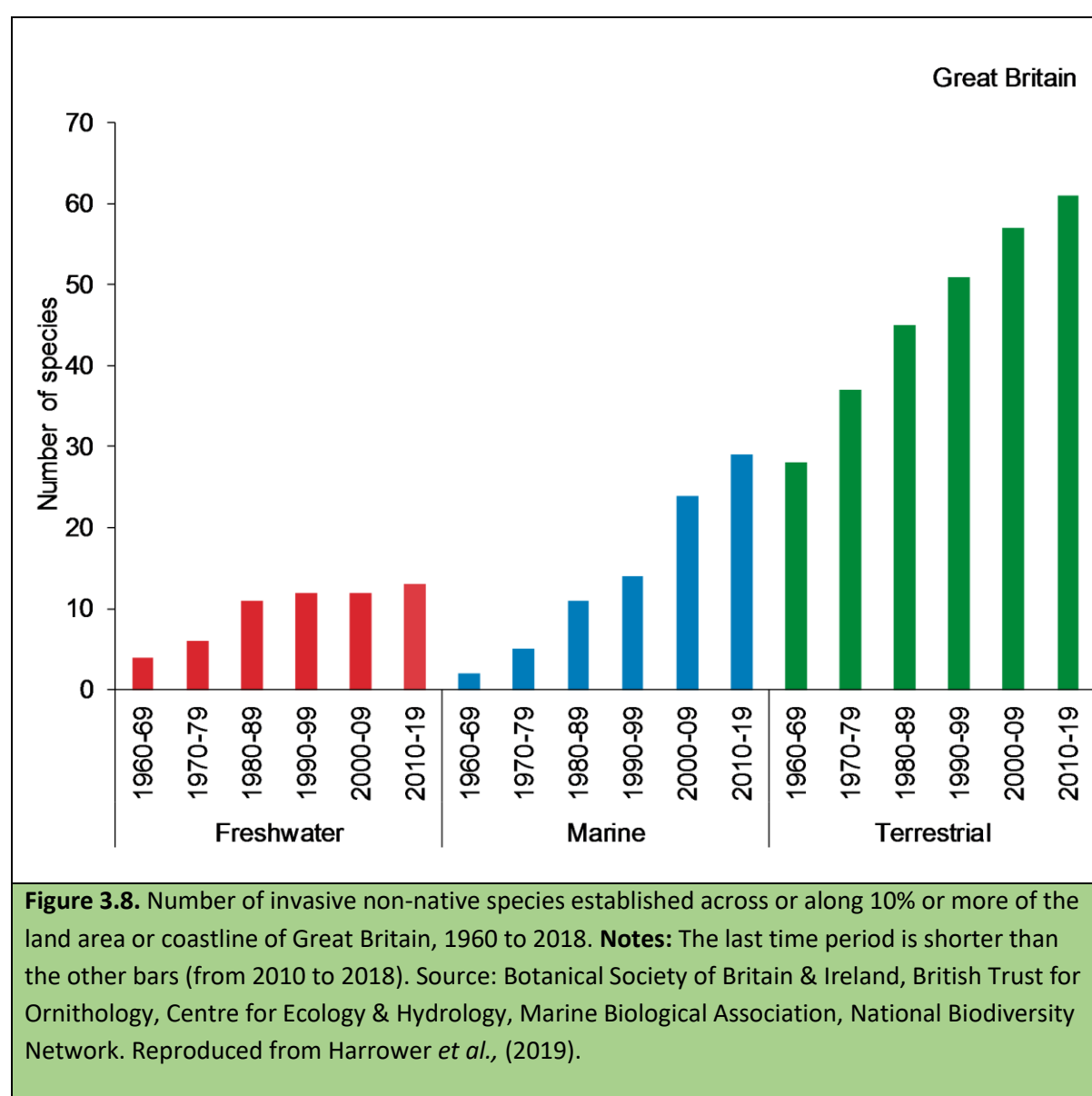
The UK Plant Health Risk Register (UKPHRR) provides a major resource for assessing current and future pest and pathogen risks (<https://secure.fera.defra.gov.uk/phiw/riskRegister/>). It was developed by Fera and Defra in 2013 based on recommendations of the independent Task Force on Tree Health and Plant Biosecurity and launched in 2014. The UKPHRR records and rates risks to UK crops, trees, gardens and ecosystems from plant pests and diseases and currently (29<sup>th</sup> January 2021) includes records of 1227 pests and pathogens. It provides a framework for decisions on priorities for actions by government and plant health stakeholders. For example, the number of high priority forest and woodland pests derived from the UKPHRR is utilised as one of the Forestry Commission Key Performance Indicators (Forestry Commission, 2020a).

Official statistics from the UK Biodiversity Indicators (Defra, 2020a) show a progressive increase, since 1960, in the number of INNS recorded in freshwater, marine and terrestrial environments across Great Britain (Figure 3.8), which is likely to have increased pressure on native species and habitats (Harrower *et al.*, 2019). Of the 3,208 non-native species recognised and recorded in Great Britain from 1960 to 2018, 62.5% are classified as established (reproducing in the wild) and 193 species are thought to exert a negative impact on native biodiversity (46 freshwater species, 39 marine species and 108 terrestrial species). Terrestrial environments have seen the highest number of recorded INNS, 58, between 2010 and 2018.

The Global Assessment report on Biodiversity and Ecosystem Services identifies INNS as one of the top five threats to biodiversity worldwide (IPBES, 2019). The UK Biological Security Strategy (The

Home Office, 2018), which brings together cross-Government initiatives to protect the UK and its interests from significant biological (human, animal and plant) risks, notes that between August 2000 and December 2017 there were 22 outbreaks of exotic notifiable animal diseases in the UK that cost the Government between £300,000 and £3 billion. INNS potentially cost the UK economy £1.7 billion per year (£1.3 billion to England, £0.24 billion to Scotland and £0.13 billion to Wales) (Williams *et al.*, 2010).

CCRA2 highlighted risks from pests and pathogens as a priority area for future research (CCC, 2017. Although there has been further research, especially on high-risk pest and pathogen species, it is not clear from the evidence whether subsequent research was directed based on the CCRA2 recommendation or in response to heightened risk status.



### 3.3.1.2 Future risk (N2)

Risks from pests and pathogens are expected to continue increasing across all UK countries in response to expanding trade and changing climate. Uncertainties relating to post-EU-exit trade agreements and cross-border biosecurity cooperation, especially between EU nations, make it difficult to assess the future level of risk. A level of continuity has been assured by a Government statutory instrument, included under the correcting powers set out in Section 8 of the EU Withdrawal Act 2018, which ensures maintenance of existing INNS safeguards for those species listed on the EU Invasive Alien Species regulation after EU-exit (<https://www.theyworkforyou.com/lords/?id=2019-01-22a.662.3>). Existing domestic regulations will continue to safeguard against other INNS not covered by this EU regulation. Increased imports of high-risk commodities, such as wood products and live plants (especially exotics), or from regions with high pest or pathogen prevalence, would increase the chance of INNS entering the UK and potentially becoming established. For example, in 2012 an outbreak of Asian Longhorn Beetle (*Anoplophora glabripennis*), a native of Southeast Asia and serious pest of broadleaved trees, was discovered in Kent, England, and attributed to untreated wood packaging from a nearby business importing stone from China (Straw *et al.*, 2016).

COVID-19 poses additional challenges and uncertainties for managing pest and pathogen risks, particularly ensuring biosecurity measures are maintained to safeguard the UK food supply chain whilst ensuring the safety of surveillance teams involved. As well as guidance and support provided by UK Government, specific guidance has been provided by pest management organisations, including “Becoming COVID-19 secure” by the British Pest Control Association (BPCA, 2020). Recent updates to the UK climate projections, UKCP18 (Lowe *et al.*, 2018 Murphy *et al.*, 2018), highlight continued warming and changing patterns of extreme events across the UK, which will impact on the life cycles and population dynamics of many pests and pathogens, as well as host species (Boggs, 2016). Warming is likely to expand the range of climate suitability for many species and increase the chance of establishment of INNS in the UK, particularly for species that have shown recent northward expansion across Europe. For example, Bradshaw *et al.* (2019) projected that with 2°C - 4°C global warming<sup>4</sup> there is a high risk of the tobacco whitefly (*Bemisia tabaci*) becoming established in the UK. Milder winters are also expected to encourage overwintering and expansion of species currently limited by cold temperatures, such as Diamondback Moth (*Plutella xylostella*) (Wainwright *et al.*, 2020). *Xylella fastidiosa* is also a significant future risk with multiple plant host species of economic and environmental importance (White *et al.*, 2019). Future climate changes are also likely to increase stress on some terrestrial species and habitats, which can lead to reduced resilience to other stresses, including pest or pathogen attack (Dutta *et al.*, 2020).

Many pests and pathogens respond to thresholds of temperature, moisture availability and wind (speed and direction), which are some of the more uncertain climate parameters in future climate projections. Life cycle and phenology responses occur at community scales, and are, therefore, subject to community effects, such as competition, as noted for non-pest species (see Risk N1).

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<sup>4</sup> HadGEM3A-GA3.0 atmosphere model driven by sea surface temperature patterns from 6 CMIP5 projections, using timeslices at 2°C global warming as described in Betts *et al.* (2018) and at 2°C global warming using the same method.

Continued climate changes may also induce complex interactions between pests/pathogens and their host species, leading to compound responses. For example, with simulations of the productivity and interactions of ash trees and *Hymenoscyphus fraxineus*, the fungus responsible for ash dieback, across Europe with global warming of approximately 2°C and above 4°C at the end of the century<sup>5</sup>, it was projected that by 2050 ash productivity, taking account of the negative impact of *Hymenoscyphus fraxineus*, may increase between 15-50% (Goberville *et al.*, 2016). This was due to the projected higher temperatures encouraging ash growth and dryer summer conditions constraining fungal growth (CCC, 2019b). Crop pests and pathogens have shown an average poleward shift of 2.7+/-0.8 km per year since 1960, consistent with climate change drivers, e.g., warming (Bebber *et al.*, 2013). These trends would be expected to continue with further climate change, leading to more frequent incursions of INNS into the UK, particularly in south-eastern England where average temperatures are warmer and the close proximity to Europe results in some species being introduced by suitable wind patterns (Burgin *et al.*, 2017). Some endemic species that are currently not invasive may become invasive as a result of future climate change. In Wales, invasive species (such as rhododendron) may extend their range to higher elevations in upland western areas due to higher temperatures (Berry *et al.*, 2019). The risk posed by *Dothistroma* needle blight, a major pathogen of Scots pine trees, is also expected to increase under projected climate change, leading to reduced growth and carbon sequestration of Scots pine stands across Wales, northern England and particularly Scotland (Jones *et al.*, 2020).

Uncertainties in species and habitat responses to future climate changes are compounded by large uncertainties in future human interactions, such as biosecurity practices, land-use change, trade patterns and habitat connectivity. Also, the threat posed by cryptic diseases, i.e., those that are difficult to detect (such as phytophthoras) will continue to be difficult to assess. There is much less evidence on the cascade of risks relating future potential climate-pest/pathogen changes to risks for natural terrestrial species and habitats, e.g., relating to key species and their ecosystems (Mitchell *et al.*, 2019). Further details on pests and pathogens of specific relevance to agriculture and forestry are provided in Risk N7 (Risks to agriculture from pests, pathogens and invasive species) and Risk N8 (Risks to forestry from pests, pathogens and invasive species).

### 3.3.1.3 Lock-in and thresholds (N2)

Many pests and pathogens are more difficult and extremely costly to manage once established and widespread across a region (Watkiss *et al.*, 2019). These lock-in risks are often initiated by thresholds (see below), emphasising the importance of enhanced surveillance and other biosecurity measures to facilitate rapid and effective responses and build long-term resilience in native species and habitats. Poor regeneration of key species as a result of pest or pathogen impacts may also risk the sustainability of native species and habitats. For example, the Native Woodland Survey Scotland highlighted the impact of *Dothistroma* needle blight on young Caledonian pine woodlands in Scotland as a factor in the recent poor regeneration levels that threaten sustained woodland growth (Forestry Commission Scotland, 2014).

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<sup>5</sup> 7 CMIP5 climate models with the RCP2.6 and RCP8.5 concentrations pathways.

Incursions and outbreaks of pests and pathogens are often initiated by the crossing of thresholds, and events. These include human-induced events, such as shipments of infected goods or outbreaks across protected zones, and climate-induced events where pests or pathogens respond to climate variations. For many species, accumulated temperature thresholds regulate the timing of life cycle events and population growth, e.g., Berryman, 1982; Reed *et al.*, 2018. Temperature and photoperiod thresholds are particularly important for the survival and population dynamics of many species, and some, such as mosquitoes and ticks, are also sensitive to moisture availability (Metelmann *et al.*, 2019). Wind speed and direction also exert a major influence on the spread (including incursion into the UK) of some species, e.g., the Diamondback Moth (Wainwright *et al.*, 2020). One of the case studies detailed in a report on climate-driven threshold effects in the natural environment, commissioned by the CCC (Jones *et al.*, 2020), shows that future higher temperatures would be expected to increase incidence of the sheep parasite (*Haemonchus contortus*) across all regions of the UK, with up to 1.6 million lambs affected and estimated annual economic losses of up to £10.2 million depending on the region (see Risk N7 for more details). As climate change progresses, the likelihood of passing climate-related thresholds increases, which would increase the risk magnitude score.

#### 3.3.1.4 Cross-cutting risks and inter-dependencies (N2)

Outbreaks have implications for native species composition and carbon sequestration potential. Changes in trophic level interactions, e.g., predator-prey relationships, affect the resilience of individual species and habitats (Thackeray *et al.*, 2016) and the character and appearance of landscapes. Severe damage or collapse of keystone species may threaten large-scale ecosystems and their services (Mitchell *et al.*, 2019). There are strong interdependencies between trade movements and the risk of incursions and spread. There are also cross-cutting risks and interdependencies across health sectors (plant, animal and human health), such as common vectors for transmission and management approaches. The UK Biological Security Strategy (The Home Office, 2018) highlights that around 60% of all human diseases and 75% of new and emerging infectious diseases are zoonotic (naturally transmitted from other animals to humans), and plant and animal disease outbreaks can have significant effects on the environment and human health.

#### 3.3.1.5 Implications of Net Zero (N2)

The Net Zero target will involve major land-use change, which will affect terrestrial habitats. This will influence the level of risk from pests and pathogens. This will depend on how Net Zero translates into land-use change for managed and unmanaged terrestrial habitats and their subsequent management.

Increases in the abundance of pests or pathogens or in the frequency of outbreaks are likely to reduce plant productivity and divert resources from woodland expansion objectives, making it more difficult to reach Net Zero. This is particularly relevant to woodlands and the forestry sector because woodland expansion and afforestation targets are central to the Net Zero scenario (see Risk N8). Afforestation includes risks from importing tree species and/or planting non-native species, which may introduce or promote the establishment of new pests or pathogens. Also, expansion of wooded areas is likely to increase connectivity of habitats and facilitate the spread of pests and pathogens,

particularly invasive species, across the landscape. In Wales, efforts to reduce emissions from peatlands could be undermined by climate change leading to more effective seedling of Sitka spruce leading to it becoming invasive on adjacent peatlands.

### 3.3.1.6 Inequalities (N2)

There are likely to be inequalities in the risks from pests or pathogens. Proximity to major import locations and/or continental Europe increases the risk from INNS, either as a result of imported goods or incursions from the near continent. Some sectors, habitats and species are also more at risk than others, including agriculture and forestry (see Risks N7 and N8), native woodlands and ash trees (see above on current and future risks).

### 3.3.1.7 Magnitude scores (N2)

**Table 3.5** Magnitude scores for risks to terrestrial species and habitats from pests and pathogens, including Invasive Non-Native Species .

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
<b>Northern Ireland</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
<b>Scotland</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
<b>Wales</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)

Notes: Magnitude categories based on the level of agreement of the evidence and expert judgement of authors (in agreement with CCRA reviewers) of medium for the present day with intermediate impacts on or loss of species groups and medium for the future for Northern Ireland, Scotland and



Wales. England is scored as high for the future (major impacts), due to its closer proximity to continental Europe and the higher potential increase in the incursion and establishment of INNS. All countries are high for the 2080s for the pathway to 4°C global warming at the end of the century, due to an increasing risk posed by higher temperatures.

### **3.3.2. Extent to which current adaptation will manage the risk or opportunity (N2)**

#### **3.3.2.1 Effects of current adaptation policy and commitments on current and future risks (N2)**

##### **3.3.2.1.1 UK Wide**

There are a wide range of biosecurity policies and commitments in place to support the management of pest and pathogen risks in the UK. At the international scale, these include multilateral agreements to encourage cooperation and coordination of biosecurity activities among nations and organisations. For example, the International Plant Protection Convention (IPPC) and the World Organisation for Animal Health (OIE) aim to prevent the introduction and spread of plant and animal pests and diseases through development of standards and coordination of biosecurity activities across members. International environmental agreements, such as the UN Convention on Biological Diversity and the Bern Convention, also consider aspects of pest, pathogen and climate change management within the wider context of biodiversity and nature conservation.

Decisions on implementing biosecurity measures in the UK have been made predominantly at EU level, with plant and animal biosecurity in the UK currently following EU legislation. For example, under EU Plant Health Regulations tighter controls have recently been imposed on the import and movement of plants and plant materials in response to heightened risks (House of Lords, 2018). The UK benefits from coordinated EU-wide intelligence gathering, disease notification systems, plant and animal movement tracing systems and coordinated research on pests and pathogens. Post-EU-exit, the UK is no longer automatically part of this framework, and it has been emphasised that continued cooperation and sharing of intelligence between UK and EU are essential to adequately manage the UK's current and future biosecurity risks (House of Lords, 2018).

Within the UK, there is a strong policy framework in place to manage current and future pest and pathogen risks (although our view is that this is less well developed for INNS). This is supported by robust science, including recent recommendations from 'Animal and Plant Health in the UK: Building our science capability report' (GO-Science and Defra, 2014) and subsequent 'Vision and high-level Strategy for UK Animal and Plant Health Research to 2020 and Beyond' (BBSRC, 2016). The UK Biological Security Strategy (HMG, 2018a) also sets out a wide range of activities across Government to protect UK citizens and British interests from significant biological risks, including those posed by pests and pathogens. It also describes four pillars for responding to biological risks: Understand; Prevent; Detect; Respond, which is a good framework for managing pest and pathogen risks in general.

Various approaches are maintained to highlight the ecosystem service value of forest stocks and trees, and therefore provide an indication of the potential losses from pests and pathogens. These include the Office for National Statistics' UK Urban Natural Capital accounts or woodland accounts, Forestry England's annual natural capital accounts, Nature Scotland's national capital accounts, and

the i-Tree Eco tool which has been used in various cities in England, Scotland and Wales to calculate and value the ecological benefits provided by peri-urban/urban trees.

For INNS, the Great Britain Invasive Non-native Species Strategy provides the framework to support coordination of policy and action across England, Scotland and Wales (Defra, Scottish and Welsh Governments, 2015). The Strategy seeks to address the potential damage from INNS through preventing the introduction of such species into the wild, rapid response and early intervention. Defra, Scottish Government and Welsh Government are working with the GB Non-native Species Secretariat to prepare risk assessments and action plans which do include climate change, as well as developing long-term horizon-scanning exercises to identify future threats.

Policies vary by sector, and the agriculture and forestry sectors have a range of policies, commitments and tools to address their specific risks which are detailed in Risks N7 and N8. Adaptation measures also vary significantly for localised or widespread outbreaks. For example, Scotland's forestry and biodiversity sectors now focus on general management strategies rather than control measures to manage the green spruce aphid (*Elatobium abietinum*), which has become widespread across the country (CCC, 2017). Other landowners, including private estates and charities, are developing approaches to manage their specific risks. For example, Historic England have mapped pests and diseases in their historic parks and gardens (Branson *et al.*, 2018) in support of their Climate Change Adaptation Plan. Also, the current status and proposed monitoring and reporting framework has been assessed for managing the threat from pests and diseases on UNESCO World Heritage Sites, historic gardens, houses and museums (Shackleton *et al.*, 2020).

Risk assessment procedures are increasingly important for identifying high-risk species and prioritising actions. For invasive species, the UK Government has put in place both horizon scanning and risk assessment programmes, which enable the identification of emerging threats due to climate change, as well as sleeper species that are already present but could become invasive in a changing climate. For example, the UK Plant Health Risk Register enables stakeholders to identify, prioritise action and evaluate potential adaptive capacity to manage pests and pathogens that threaten UK plant species and habitats. Also, dispersion modelling is used to help assess the risk of spread of some pests and pathogens such as Bluetongue virus (Defra, 2017) or foot and mouth disease (Mikkelsen *et al.*, 2003).

#### 3.3.2.1.2 England

National priorities for action on the environment and climate change are detailed in the Government's 25 Year Environment Plan (25YEP, HMG, 2018b); the overarching strategy for improving the environment in England. The 25YEP includes details on the management and reduction of the impacts of existing plant and animal diseases, reducing the risk of new ones and tackling INNS. It has a goal of enhanced biosecurity with indicators on the abatement of the number of INNS entering and establishing against a baseline and the distribution of INNS and plant pests and diseases, but this is in broader context than just climate change.

The Second National Adaptation Plan (NAP2, Defra, 2018a) included outcomes and goals for managing and reducing the impacts of existing plant and animal diseases, reducing the risk of new ones and tackling INNS. However, it has been noted that neither the 25YEP, NAP2 nor other sector-

specific plans outline measurable targets for managing and reducing the impact of existing plant and animal diseases.

The England Tree Health Resilience Strategy includes provision for assessing the efficacy of planned government action on trees (Defra, 2018c).

### 3.3.2.1.3 Northern Ireland

Northern Ireland has a range of policies for dealing with pests and pathogens (Gioria *et al.*, 2019). An Invasive Alien Species Strategy for Northern Ireland aims to address knowledge and awareness gaps, minimise arrivals and their spread, and eradicate and control INNS (DAERA, 2013). Further policies are in place for specific pests and pathogens, e.g., for ash dieback disease strict policies of eradication and containment are set out in the All-Ireland Chalara Control Strategy which are considered to have significantly prevented the rapid establishment and spread of this pathogen across Ireland (McCracken *et al.*, 2017).

In July 2020, Northern Ireland complied with the EU Regulation (1143/2014) which requires Member States to produce effective management measures for each of the selected Widely Spread Species. These measures will endeavour to minimise the potential negative impact upon biodiversity, related ecosystem services, human health and the economy that these 11 species could have: Nuttall's waterweed (*Elodea nuttallii*); Chilean rhubarb (*Gunnera tinctoria*); Giant hogweed (*Heracleum mantegazzianum*); Floating pennywort (*Hydrocotyle ranunculoides*); Himalayan balsam (*Impatiens glandulifera*); Curly waterweed (*Lagarosiphon major*); American skunk cabbage (*Lysichiton americanus*); Parrot's feather (*Myriophyllum aquaticum*); New Zealand Flatworm (*Arthurdendyus triangulatus*); Grey squirrel (*Sciurus carolinensis*); Slider terrapins (*Trachemys scripta spp.*).

Information on biosecurity risks, legislation and management options for invasive species in Northern Ireland is available *via* the Invasive Species Ireland web site (<https://invasivespeciesireland.com/>), a collaboration between DAERA and the Irish National Parks and Wildlife Service. Also, the Catalogue of pests and pathogens of trees on the island of Ireland provides a valuable baseline on plant pests in Northern Ireland and has been used to study the history of plant pest invasions in Northern Ireland including within the context of climate change (O'Hanlon *et al.*, 2020).

### 3.3.2.1.4 Scotland

The second Scottish Climate Change Adaptation Programme (SCCAP, Scottish Government, 2019) includes references to a National Species Reintroduction Forum project which is working to identify species where conservation translocation could provide various benefits including moving species away from areas of high disease risk (National Species Reintroduction Forum, 2014). SCCAP2 continues to recognise the need to tackle INNS in a variety of habitats and proposes management of INNS as a possible indicator for monitoring non-climate pressures. Prevention, control and eradication of invasive species is a major aim of Scotland's biodiversity policy and the management strategy of protected areas. As part of the Pests and Diseases Research Outcome of SCCAP2, the Plant Health Centre in Scotland have examined the effectiveness of national surveillance monitoring

options for detecting a *Xylella fastidiosa* outbreak (White *et al.*, 2019). Lawrence (2020) notes there are some concerns of over-reliance in Scottish forestry on a small number of tree species which can increase the risk from high impact tree pests or diseases.

#### 3.3.2.1.5 Wales

The latest climate change adaptation plan for Wales 'Prosperity for All: A Climate Conscious Wales' details a range of policy measures to address pest, pathogen and INNS risks (Welsh Government, 2019b).

These include a specific action *to protect our natural habitats from the increasing risks associated with INNS* and sub-actions to: a) implement actions in the GB INNS strategy; b) incorporate biosecurity measures into marine proposals to reduce the risk of introducing and spreading marine INNS; c) coordinate, set priorities and raise awareness of INNS in Wales through the Wales INNS group; and d) introduce contingency plans to respond to newly arrived INNS.

There are also a range of actions relating to tree disease (see Risk N8 for more detail on forestry) including:

- Promote the use of 'i-tree Eco' and similar tools to understand the nature and value of peri-urban/urban trees and assist in pest/disease incidence management.
- Promote resilience to increasing incidence of arboricultural pests and diseases.
- Develop and maintain a risk register of pests and diseases and their threat to tree health in Wales.

Extended surveillance to cover military and civil facilities is also under consideration (Welsh Government, 2019b).

The Invasive Non-native Species Group help identify INNS priorities and resolve issues relevant to Wales. Their members are from Wales Biodiversity Partnership, Academia, GB Non-Native Species Secretariat, Local Authorities, Natural Resources Wales, Public Health Wales, Wales Environment Link, Welsh Government, the Welsh Local Government Association and Utility companies.

#### 3.3.2.2 Effects of non-Government adaptation (N2)

Management of pest and pathogen risk within the UK is strongly coordinated and regulated through government policy, although this is not necessarily the case for INNS (Environmental Audit Committee, 2019). Non-government stakeholders, including farmers, other landowners and nature conservation groups focus on actions relevant to their specific requirements. For example, monitoring individual crops, species and habitats on a day-to-day basis for new pests and diseases, and applying measures to minimise local damage. Increasing diversity is a critical strategy available to non-government stakeholders to increase overall habitat resilience to a wide number of potential risks, as well as delaying or reducing the build-up of pests and diseases within a habitat. Commercial agricultural companies provide a range of tools and advice to support large agricultural organisations and smaller farmers to manage pest and pathogen risks. Advice and guidance on pest

and pathogen risks and management options are also available through trade magazines. For woodland management, interventions that include assisted migration of species from locations with climates closer to the future projections have been suggested, where this is shown to be effective and meet the objectives for the woodland (Forestry Commission, 2020b). There is also potential for 'natural regeneration' approaches to afforestation that reduce reliance on imported samplings and therefore the risk of introducing pests and pathogens.

### 3.3.2.3 Barriers preventing adaptation (N2)

Effective adaptation requires clear understanding of the risks and interactions, available tools and techniques and suitable funding and policy programmes to enable adaptations. The following barriers may prevent appropriate adaptations to pest and pathogen risks from being realised:

- **Research and understanding:** Complexity in the relationships between biotic and abiotic factors influencing pest or pathogen risks can be a barrier to understanding appropriate adaptation measures, and defining measurable goals (CCC, 2019b). Understanding cryptic diseases, i.e., those that are difficult to detect (such as phytophthoras) poses a particular constraint on adaptation actions.
- **Surveillance and inspections:** Adaptation actions may be limited by insufficient inspectors at borders and across the UK and by post-EU-exit restrictions in international collaboration and access to international pest surveillance and early warning data, e.g. the Animal Disease Notification System (ADIS, [https://ec.europa.eu/food/animals/animal-diseases/not-system\\_en](https://ec.europa.eu/food/animals/animal-diseases/not-system_en)). Adaptations for INNS may be particularly limited as there are no existing inspectors for INNS, compared with the established inspectorates for animal, plant, fish and bee health (<https://publications.parliament.uk/pa/cm201919/cmselect/cmenvaud/88/8805.htm>).
- **Funding:** Long-term adaptations e.g., breeding programmes typically have high up-front costs that benefit multiple sectors and stakeholders. It is difficult to quantify the benefit for each sector/stakeholder, which can result in inaction. A recent UK Government Environmental Audit Committee report identified lack of resources as a critical barrier to tackling INNS, noting that only 0.4% of the total annual GB expenditure on biosecurity (approximately £220 million) is spent on INNS. The CCC (2019b) report identified funding and resources as common barriers for adaptation projects in England. They suggest that Government should consider how to de-risk development of funding bids for larger adaptation projects and reduce barriers to accessing such funds.
- **Policies:** Government policies should provide clarity and support for adaptation. Barriers may exist due to inadequate policies and legislation driven in our view by a lack of requirements to include adaptation across the board, and a lack of political leadership to mandate this.

This is also an area where there is a strong justification for Government intervention, especially in terms of legislative control, monitoring and surveillance, and support when outbreaks occur (to minimise spread).

### 3.3.2.4 Adaptation shortfall (N2)

There are risk assessments and a wide range of management measures in place to provide some adaptive capacity to reduce the increasing risks from pests and diseases driven by climate change, but by comparison there are few for INNS in our view, hence our assessment is that the risk is being partially managed across the UK (Table 3.6). There is a compelling need for enhanced monitoring, surveillance and early response measures to prevent a future spread of native pests and pathogens and the establishment of INNS.

### 3.3.2.5 Adaptation Scores (N2)

<b>Table 3.6</b> Adaptation scores for risks to terrestrial species and habitats from pests and pathogens, including Invasive Non-Native Species			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)

### 3.3.3 Benefits of further adaptation action in the next five years (N2)

The economic and environmental costs associated with managing established pests and pathogens are considerably higher than the costs of biosecurity measures to prevent INNS becoming established in the UK (SRUC, 2013). Therefore, further adaptation actions focusing on enhanced prevention (e.g., pathway management), monitoring, surveillance and early response are considered highly beneficial (CCC, 2019b).

Increased horizon scanning for INNS and improved coordination with international pest risk surveillance organisations would help the UK to manage risks associated with changes in the post-EU -exit trade portfolio and projected climate changes. Research since CCRA2 has highlighted various adaptation options and benefits, e.g., in Northern Ireland, recent research recommends that increasing abundance, diversity and care of tree standards in hedgerows would mitigate the impact of tree diseases on the ecosystem services provided by hedgerows on farmland (Spaans *et al.*, 2018).

Further research on the likely responses and resilience of native species and habitats to pest and pathogen risks, and adaptation options to manage these risks, will help inform suitable adaptation decisions. Further research on the implications of projected climate changes within the context of potential changes in trade and other drivers would help understand the primary drivers of future change and plan adaptations appropriately. In general, there is scope for more integrated cross-sector policy initiatives, e.g., across agriculture, forestry, natural environment and human health, to implement good practices and share tools and resources (HMG, 2019; Baylis, 2017).

### 3.3.3.1 Indicative costs and benefits of additional adaptation (N2)

There is a strong economic case for greater Government intervention in research, monitoring, awareness raising and coordination of reactive response to potential and emerging threats (including invasive species) based on case study analysis of four major pests and pathogens *Phytophthora ramorum*, Ash dieback, *Dothistroma* Red needle blight and *Septoria*, a winter wheat yellowing fungus (see Watkiss *et al.*, 2019). Although this would require additional Government action, Watkiss *et al.* (2019) project that the economic benefits are high compared with the costs (at least 10:1). Given reasonable assumptions on the spread of these four diseases, they estimate the additional damage costs (2018 constant prices, discounted) from climate change by 2050 to be increasing by £67.5 million for *Phytophthora ramorum*, £178 to £596 million for Ash dieback, £300 million for *Dothistroma* and decreasing by £83 to 245 million for *Septoria*.

There is a clear a role for public co-ordination of research, monitoring and surveillance. Previous analysis by SRUC (2013) has identified that investment in monitoring for pests has a high benefit-cost ratio of around 10:1. There are also clear benefits from Government investing in information about pests and pathogens – their spread, likely impacts, and treatment methods – as this information flow would not otherwise occur. Whilst a large proportion of the costs (or pests and pathogens) may be borne by private land-owners, public support is likely to be needed where there are local concentrations of economic activity that are threatened by the rapid spread of one of these pathogens in an area (to reduce the much larger costs once pests and pathogens become established). This economic argument is strengthened by climate change because the future nature of the threats will be less understood by private actors' past experience.

### 3.3.3.2 Overall urgency scores (N2)

<b>Table 3.7</b> Urgency scores for risks to terrestrial species and habitats from pests and pathogens, including Invasive Non-Native Species.				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Medium	Medium	Medium

Because the magnitude of future risks is high for all countries in the 2080s under a 4°C world, and the view that current adaptation plans will only partially manage the risk, additional intervention is needed to better manage future potential impacts, this risk has been scored as more action needed.

### 3.3.4. Looking ahead (N2)

Enhanced monitoring, surveillance and early response measures are needed to manage the risk to UK terrestrial species and habitats from pests and pathogens, especially in view of the need for improved international coordination following EU-exit. Regulations and resources will need to keep pace with the increasing risks and management measures required and consider the changing

portfolio of risks e.g., from INNS relative to native species. A range of interventions are available to manage future climate change risks to species and habitats, including assisted migration and increasing diversity. Management actions need to be supported by biosecurity strategies and policies that improve protection from high-risk activities, including plant sales, aquaculture, transport of live animals and plants and their products. Further research is required to understand specific climate responses and thresholds of high-risk pest and pathogen species, and the potential change in risk associated with different adaptation options. UK mapping of multiple pest and pathogen observations would support communications on risk across administrations and organisations within the UK. There is also scope for improved collaboration across biosecurity sectors (plant health, animal health, human health and INNS) and with relevant disciplines e.g., meteorology (Hemming and MacNeill, 2020), providing increased capability and resource sharing.

### 3.4. Opportunities from new species in terrestrial habitats colonisations (N3)

- Opportunities are unlikely to be fully identified currently, as some classes of organisms are more studied and visible (e.g., birds).
- Whilst species may have suitable climate space, they may not have moved into it yet due to their lack of mobility (adaptive capability) or the absence of other requirements.
- Current and future opportunity is assessed by experts as medium but increasing to high for a pathway to 4°C global warming at the end of the century, as there are greater opportunities for range expansion.
- Further investigation is needed to identify species for which climate change would represent an opportunity and to understand the implications of their arrival into new areas or habitats, whilst considering how to integrate them into future conservation planning.

#### Introduction

CCRA2 assessed the opportunities from new species colonisations (CCRA2 Risk Ne2), concluding that more action was needed in terms of building coherent ecological networks and factoring climate change into conservation planning. As identified in Risk N1, while a number of terrestrial species and habitats are at risk from climate change, there are those that could benefit. Opportunities of climate change will be taxon and species specific, with more mobile species likely to be more responsive. Climate change, especially increasing temperatures, can provide the opportunity for increases in populations, as well as leading to species moving and / or expanding their ranges northwards or to higher altitudes. Thus, they have the opportunity to colonise new areas. This can take two forms, firstly the species can be new to Great Britain or Ireland, although the level of migration is restricted as both are islands. Secondly, the species may be new to a UK country or region. If the new species interacts negatively with native species, or alters habitat condition, then it is considered an INNS or pest (Risk N2). In more positive cases, new species can enhance species richness and contribute to community adaptation to climate change. Also, while both of these can be consistent with climate change, often it is a complex situation involving other drivers. There is also the possibility of migrant



species becoming resident in an area, thus enhancing its biodiversity, providing they do not negatively compete with native species, for example, for limited winter food supplies.

### 3.4.1 Current and future level of opportunity (N3)

Note: currently available evidence is not sufficient to allow us to report on the current and future level of opportunity, for each UK country separately.

#### 3.4.1.1 Current opportunity (N3)

New species are migrating into the UK (Hubble, 2014; Gurney, 2015) and, while it is often consistent with climate change, especially if they have come from the continent, it is often difficult to attribute this to climate change, with humans more often implicated in the arrival of new species. Given suitable habitat, it is likely that they will expand their range and there is potential for them to become invasive (see Risk N2).

While there is a mixed response to climate change within and across taxa, some, such as mammals show an overall net positive response (Burns *et al.*, 2016). This may be dependent on factors such as geography, ecology of the species and habitat changes, but the threat posed by climate change to many species (Risk N1) should not be underplayed. Analysis of northern range margin changes of 1573 southerly-distributed species from 21 animal groups in Great Britain over the past four decades found that, while most ranges shifted northwards in both the two time periods, some (e.g., macromoths) shifted southwards in one of the time periods (Mason *et al.*, 2015). In the more recent time period, macromoths and butterflies have moved north faster. While Fox *et al.* (2014) found an overall decrease in frequency of occurrence across 673 macromoth species in Great Britain, 160 species, mostly in southern Britain, showed an increase consistent with climate change. A decrease in overall moth abundance (based on 176 species) similarly was found for Scotland, but estimated population trends were positive for 29% of species (Dennis *et al.*, 2019). An occupancy indicator (based on 230 species) showed a 16% increase for 1990–2014. In both cases climate change was suggested as a possible driver, although for some moth species, especially those that use conifer woodlands, changes in land use and management may have contributed to their positive response.

An assessment of latitudinal and elevational shifts in range margins of 80 breeding bird populations in Great Britain between 1994–2009, showed poleward shifts in the leading (northern) range margin were greater than those of the range-centre, while the trailing range (southern) margin was largely static (Massimino *et al.*, 2015). Thus, there was significant range expansion, with the expansion lagging behind the changes in temperatures. The results held even for (rarer) species for whom range contraction might be expected. A mixed response was found to change in elevation. Gillings *et al.* (2015) analysed the range shifts of the distributions of 122 species of British breeding birds during 1988–1991 and 2008–2011 and a full range of directional axes. They estimated a 13.5 km shift northwards had occurred, but that the directions of species' range centroid shift were not correlated with spatial trends in any single climate variable. This suggests that range shifts of British birds are multidirectional, individualistic and probably determined by species-specific interactions of multiple climate factors, with a consequence for change in community composition.

A literature and expert-based review of the drivers of change across 322 species sampled from a broad range of taxonomic groups in the UK found that increasing climate change was the most positive driver species population changes (~1970–2012) for invertebrates and vertebrates (Burns *et al.*, 2016). Many mobile species with southern distributions are increasing and colonising new areas. In the case of once rare species, such as the Dartford warbler, it continues to be limited by cold winters (Bradbury *et al.*, 2011), most recently in 2009/10, it is increasing in numbers and expanding its range (Green, 2017). This is attributed to milder winters (Hayhow *et al.*, 2017). Resident species, such as great tits, robins, dunnocks and wrens, also seem to be benefitting from the warmer winters and springs. Milder winters are also leading to increased populations of short-distance migrants, such as chiff chaffs and blackcaps and to the expansion of their range northwards and to higher altitudes.

Butterflies and moths have been shown to respond more to changes in seasonal temperatures, with the spatial variation in the community composition of moths being associated with winter and summer temperatures and butterflies with winter and autumn temperatures (Martay *et al.*, 2016). As seen for other taxa, current increases in these seasonal temperatures will have benefited certain species.

The expansion of some rare species also has been postulated to be associated with climate change (e.g., ambrosia beetle in the Wye Valley SAC; Alexander, 2019), whilst the increase of some bryophytes in Wales have been associated with decreased sulphur dioxide pollution combined with climate change (Motley and Bosanquet, 2017).

Species will not only be affected by mean or seasonal climate changes, but also by extreme climatic events. These can lead to a population explosion, which may lead to positive long-term population trends in birds, although no evidence was found for butterflies and moths (Palmer *et al.*, 2017). Climate, however, is only one of a number of interacting factors that will affect the ability of species to realise the opportunity presented by increased suitable climate space. Platts *et al.* (2019) found that in Great Britain, across 13 invertebrate taxa, up to half of the observed variation in rates of range margin shift) between 1976–1990 and 2001–2015 could be explained by habitat-climate interactions, with habitat availability constraining climate driven range margins shifts. While an analysis of the roles of abundance trends, habitat availability and dispersal capacity in the range changes of 25 British southerly distributed butterfly species during two periods found that for species with stable abundances whose ranges are already expanding, management such as habitat restoration/creation may increase their rates of expansion (Mair *et al.*, 2014). However, for species with declining abundances, management to stabilise and increase abundance trends within the core of species' ranges is required first.

Thus, a number of opportunities across a range of taxa have been identified of species expanding their range and population numbers, which are, at least partly, driven by climate. Species arriving in Great Britain are likely to have come from the continent, and, based on evidence for Invasive Non-native Species they are more likely to arrive in southern Britain (Gallardo and Aldridge, 2013; 2015). For species expanding their range polewards in Great Britain, they will progressively move

northwards, reaching Scotland if suitable climate space and other factors permit. The same would apply for the Republic of Ireland and Northern Ireland. The situation for Wales is less clear. Population changes are likely to be more species specific, although Hayhow *et al.* (2017) showed that increases in populations of some resident birds (e.g., great tits, robins, dunnocks and wrens) have been greatest in Northern Ireland, followed by Scotland, with no significant difference in England and Wales. This is thought to be due to improving climatic conditions in the north and west.

#### 3.4.1.2 Future opportunity (N3)

Based on what is currently happening, it is likely that climate change will continue to offer opportunities to some, especially mobile, species, which have suitable habitats and food sources in their potential new climate space. However, some will not be able to fulfil their dispersal potential for a number of reasons, including lack of a supply of migrants, dispersal routes and suitable habitat availability (Mair *et al.*, 2014). Modelling undertaken for CCRA2 projected a potential for new suitable climate space under 2°C and 4°C scenarios for many species in the UK, especially in northern England and Scotland. This is largely a result of warmer mean temperatures. Recent publications are consistent with this. For example, a simple analysis (based solely on climate) of 3048 species from a range of taxa, compared projected future distributional changes with recently observed changes and found that, under a scenario of 3°C global warming by 2100<sup>6</sup>, climate change could represent a medium or high opportunity for 54% of species in Great Britain through increased suitable climate space (Pearce-Higgins *et al.*, 2017). The taxonomic variation in the proportion of species with opportunities varied from 37% for bryophytes to 90% for wasps. An association of species with habitats indicated that the opportunities were evenly distributed, apart from upland, where risks substantially outweighed the opportunities. A more comprehensive analysis of 402 species that took into account some of the other factors that affect species' distributions and response, showed that a scenario of 3°C warming by 2100 could represent an opportunity for 42% of them, with ants and wasps potentially benefiting the most (Pearce-Higgins *et al.*, 2017). The study concluded that climate change appears to represent an opportunity for more species than a risk, as more species are at their northern range margins in Britain than at their southern range margin. However, there is evidence that as richness increases homogenisation of communities may occur due to the spread of more generalist species and the decline of more specialist ones (Platts *et al.*, 2019; Harrison, 2020). Also, as already identified, climate is only one factor that affects species response to climate change.

Modelling of changes in suitable climate for birds under the future 3°C warming scenario projected that some birds (such as melodious warbler, short-toed eagle, red-backed shrike, short-toed tree creeper) potentially could establish (or re-establish) regular breeding populations in Britain in the next few decades at least partly as a function of climate (Ausden *et al.*, 2015; Hayhow *et al.*, 2017). For some, this will be moderated by habitat availability or adverse impacts of climate change on the habitat. Massimino *et al.* (2015) modelling changes in climate suitability for 124 bird species in Great Britain with a scenario of approximately 4°C global warming by 2100<sup>7</sup> also suggested it could increase for 44% of species by 2080, with 15% of species projected to increase by 2080 currently red-listed (high conservation concern) and 13% amber-listed (medium conservation concern). The largest increases were projected for the north and west, especially in Scotland, whilst declines in

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<sup>6</sup> UKCP09 probabilistic projections with the low (SRES B1) scenario

<sup>7</sup> UKCP09 spatially coherent projections with the SRES A1B scenario

red-listed species were widespread, but with gains in Scotland. Thus, turnover is also higher in the west of Britain due to large changes in species already present (see Figure 3.5 and Figure 3.6 in Risk N1).

Some opportunities identified for Welsh landscapes include warmer mean temperatures lengthening the growing season and enabling trees, grasses and shrubby plants to grow at higher elevations, resulting in a raising of the moorland line (Berry *et al.*, 2019). This could lead to the expansion of grazing and an increase in grassland productivity, but this could be at the expense of semi-natural habitats, such as upland heath. Broadleaved tree species are likely to be more widespread in central and eastern Wales, which could present an opportunity for increased timber production, carbon sequestration and woodland habitat expansion for conservation.

#### 3.4.1.3 Lock-in and thresholds (N3)

The arrival of new species may not be taken into account in protected site designations and boundaries and thus lead to uncertainty about their condition for conservation. It may take time for the necessary changes to be made.

Each species has bioclimatic constraints, but in the case of opportunities these are unlikely to be reached, unless extreme events cause local extirpations. The benefits are likely to increase with the higher emissions scenarios and over time, providing a critical upper threshold is not reached.

#### 3.4.1.4 Cross-cutting risks and inter-dependencies (N3)

New terrestrial species, either arriving from the continent or migrating from southern areas, might have the potential to become invasive. If they are invasive then it is highly likely that they will negatively impact native biodiversity, in which case they would come under Risk N2. However, for colonisation and migration these species will require suitable habitat/host species, which may not be present, particularly for colonisations in southern England from continental Europe.

Management of flood risks could affect the habitat availability and/or connectivity, with nature-based solutions and natural flood management potentially enhancing the realisation of the opportunities for species.

#### 3.4.1.5 Implications of Net Zero (N3)

This opportunity is unlikely to affect the achievement of the Net Zero target, but the migration of species could be enhanced by the associated afforestation and peatland restoration measures and the changes in agriculture practices leading to the provision of more and/or better habitat. These, combined with actions to increase habitat connectivity, including hedgerow planting, and buffer strips could increase rates of species colonisation for species of limited mobility. Also, it could provide an opportunity for planting new, climate adapted species. For tree planting, this would depend on where and how it is carried out; semi-natural woodland with a mixture of native species will benefit more species than monocultures and non-native species, which could result in the fragmentation of native habitats. There is a possible increased threat to certain habitats from bioenergy.

## 3.4.1.6 Inequalities (N3)

No inequalities were identified in relation to opportunities to terrestrial species and habitats from climate change.

## 3.4.1.7 Magnitude scores (N3)

<b>Table 3.8</b> Magnitude scores for opportunities from new species in terrestrial habitats colonisations .					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
<b>Northern Ireland</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
<b>Scotland</b>	Medium (High confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
<b>Wales</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)

Notes: Magnitude categories based on some independent evidence and the expert judgement of authors (in agreement with CCRA reviewers) of medium for the present day and, therefore, likely medium magnitude of opportunities for species groups (category: 'Intermediate opportunities for species groups') but increasing to high for 4°C world as there are greater opportunities for range expansion.

### 3.4.2. Extent to which current adaptation will manage the opportunity (N3)

#### 3.4.2.1 Effects of current adaptation policy and commitments on current and future risks (N3)

The adaptation policies and actions relevant to reversing declining trends in native species (see Risk N1) are also applicable to facilitating the realisation of climate change driven opportunities for expansion. To avoid repetition, they will not be covered here. New species and the realisation of opportunities are not (often) specific components of such adaptation plans, but they are likely to be beneficially affected by them. For example, protected areas (Sites of Special Scientific Interest) have been found to be effective for a selection of birds and butterflies expanding their range margins (Gillingham *et al.*, 2015). Habitat loss and fragmentation are important factors affecting the opportunity for species expansion to be realised. So, actions which create new habitat, either through expanding existing sites or creating new ones, or increase the connectivity between habitats (e.g., through Nature Recovery Networks) can help species to colonise new areas. Managing sites better to improve their condition can also help them to support larger numbers of species and facilitate colonisations.

Despite this, in our view there are many species of low mobility that are unlikely to be able to colonise new sites on a fast enough timescale without direct, targeted interventions (Ellis, 2015; Schloss *et al.*, 2012) including deliberate translocation, for which there is no current scheme or support across the UK, as yet. There is, therefore, an adaptation shortfall, with resources needed to facilitate the movement of species, particularly natives, whose suitable climate space is moving northwards, through, for example, more dynamic site management and planning, adaptation-related objective setting and condition assessment and targeted adaptation interventions. These should work alongside existing and planned strategies and measures (see Risk N1), which if met, could make significant steps in enabling species to migrate in response to climate change, for example through halting and reversing habitat degradation and fragmentation of the natural environment. In Scotland, a National Species Reintroduction Forum project (led by NatureScot and Royal Botanic Garden Edinburgh) is working to identify species where assisted colonisation and other forms of conservation translocation could benefit species at risk from climate change, alongside wider environmental benefits.

It will also be necessary to ensure that management plans, objectives and condition assessments of protected sites take account of new species colonisations to ensure management that supports colonisations (or in the case of invasive species, pests or diseases, prevents them), as mentioned in N1. Evidence and advice are essential to make informed decisions about these issues, and there is a lack of evidence to show that this is yet happening.

It is unlikely that EU-exit or Covid-19 will have any significant effect on the realisation of the opportunities.

### 3.4.2.2 Effects of non-Government adaptation (N3)

As highlighted above, species migration will enable some of these opportunities naturally, provided there is suitable habitat. There is unlikely to be private sector (e.g., landowners) adaptation action to facilitate these opportunities in the absence of Government action, unless they are associated with financial benefits.

Our view is that adaptation actions can happen locally on a small scale through NGOs, individual and community group initiatives, however large-scale habitat creation and improvement usually depends on government action and often are supported by government funding, such as agri-environment schemes.

The shortfall in adaptation will not be addressed by non-government adaptation alone therefore, as while many environmental NGOs and private landowners are involved in delivering adaptation measures at specific sites, generally there is not an integrated approach or a sufficiently widespread take up of appropriate actions to reduce future risk down to low levels. Contributing to the development of the ecological networks would be a useful non-governmental contribution.

### 3.4.2.3 Barriers preventing adaptation (N3)

Habitat availability, fragmentation and slow dispersal rates present challenges for species colonising new sites. The first two can be addressed by habitat restoration, re-creation and improved connectivity in areas where this is lacking for particular species. Translocation to newly available suitable sites is an option but is often considered as a last resort option because it is resource intensive and even when all the background factors are favourable, both biophysical and socioeconomic (notably land management), there is no guarantee of long-term success. Nevertheless, despite these challenges, there are now initiatives to further investigate this option with regard to newly available sites, such as the National Species Reintroduction Forum project mentioned above for Scotland.

### 3.4.2.4 Adaptation shortfall (N3)

Intervention, through actively supporting new species' colonisations, is likely to be required to realise this potential benefit in full. While general policies and programmes to improve habitat condition, extent and connectivity (see risk N1) will have known benefits for supporting species expansions and new species introductions, as stated above there are no current programmes that we are aware of that specifically support new colonisations or translocations, though work is underway (e.g. in Scotland) to assess which species could benefit from such schemes. As such, our assessment is that this opportunity is only being partially managed.

## 3.4.2.5 Adaptation Scores (N3)

<b>Table 3.9 Opportunities from new species in terrestrial habitats colonisations</b>			
<b>Are the opportunities going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
No (Low confidence)	No (Low confidence)	No (Low confidence)	No (Low confidence)

## 3.4.3 Benefits of further adaptation action in the next five years (N3)

At the time of writing, it is not possible to assess the extent of the impact that many new strategies and policy initiatives will have on adaptation, but they have the potential to be important in terms of habitat creation, restoration and connectivity. This may be further enhanced by carbon offsetting and government funding in support of Net Zero, such as through the Nature for Climate Fund. There are, however, risks, from intensive forestry and biofuel production if carbon sequestration alone is a driver. A key adaptation action that would have benefits in the next five years is to ensure join up with Net Zero mitigation policies. Other possible funding opportunities include the Government's Investment Readiness Fund (IRF) which will support the development of natural environment projects that can generate revenue from ecosystem services and attract repayable investment but could include nature-based solutions for climate adaptation and mitigation.

## 3.4.3.1 Indicative costs and benefits of additional adaptation (N3)

As highlighted above, the potential size of the opportunities involved are not well characterised, and this makes it difficult to assess the potential costs and benefits of adaptation: a low regret option would therefore be to investigate these potential opportunities, and to consider what steps might be needed to help realise the most important.

## 3.4.3.2. Overall urgency scores (N3)

<b>Table 3.10 Urgency scores for opportunities from new species in terrestrial habitats colonisations</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency Score</b>	Further investigation	Further investigation	Further investigation	Further investigation
<b>Confidence</b>	Low	Low	Low	Low

This opportunity has been scored as Further Investigation due to the low evidence of the long-term effects of new species movements into the UK, together with a lack of understanding of which specific policies would have most benefit in realising the opportunities from climate change driven



arrivals of new species in terrestrial habitats. Some research is already underway in Scotland, but this could be expanded across the UK and reflected in upcoming national adaptation programmes.

#### 3.4.4 Looking ahead (N3)

In the future, it will still be necessary to develop new approaches to establishing species in new locations and adapting conservation objectives setting and condition assessments to reflect changing distributions, for which there are no specific current plans or funding. It would also be good to consider a more systemic approach to managing biodiversity, so that opportunities can contribute to a more climate resilient future.

### 3.5. Risks to soils from changing climatic conditions, including seasonal aridity and wetness (N4)

- There is increasing evidence of the negative impacts of climate change on soil resources, often in combination with other factors (notably land use)
- Future climate projections, including UKCP18, provide strong evidence that climate risk factors will increase, including due to heavier rainfall events (erosion and compaction risks), and increased soil moisture deficits in summer (loss of biota and organic matter etc.)
- Loss of soil resources has important environmental, economic and social consequences and severe degradation of soil quality would be very likely to have long-term, potentially irreversible, implications.
- There is an urgent need for further research and comprehensive monitoring of soils to support development of sustainable soil policy initiatives.
- While there is an increased awareness of this threat, a significant shortfall remains in the adaptation responses, which are not yet commensurate with this risk level.
- Risks to soils are scored with a More Action Required category, with the magnitude of risk increasing from medium at present to high in future.

#### Introduction

As with CCRA2, risks to soils are identified as requiring more action. The magnitude of risk increases from medium at present to high in future, and, although awareness of this threat has improved, the necessary adaptation responses are not yet commensurate with this level of risk. In making this assessment, although we provide supporting quantitative evidence of the risks to key soil functions and services where possible, we have more generally applied expert opinion to distinguish the many direct and indirect effects of climate change from other drivers.

Soil health is crucial for the terrestrial natural environment. In addition to their importance for maintaining biodiversity (Risk N1 and Risk N3), soil provides multiple ecosystem services, notably for agricultural and forestry production (Risk N6 and Risk N9) for which soil fertility is extremely important, but also equally importantly in terms of regulating water flows and water quality,

recycling nutrients, and carbon storage (Risk N5), together with many other benefits including for landscape character (Risk N18) and cultural value (including archaeology).

A further crucial issue is the need for more research and monitoring of soils to support development of sustainable soil policy initiatives. The UK has over 700 soil types and many variations within those types. Soils are complex systems integrating biological, chemical and physical processes that are sensitive to climate change and other factors such as land management and pollution. Our knowledge of these processes in a changing climate and the implications for key soil properties remains a basic constraint. In particular, improved knowledge of the controlling properties and processes that regulate change (e.g., organic matter, microbial activity) would be extremely useful. In addition, measured or modelled changes in the reciprocal relationships between soil microbial communities and plant communities and their traits (Risk N1) across a range of ecosystems would be advantageous for improved understanding of changes in ecosystem functioning and regulating ecosystem services.

Regarding interactions of this risk with the co-evolving challenges of EU-exit and Covid-19, there is currently an absence of evidence. EU-exit will have an influence through its relationship with land use patterns, especially for agriculture (e.g., trade agreements; regulatory frameworks), and their impact on soils, positive or negative. For Covid-19 it is too early to infer consequences but there is some evidence that soil fieldwork including sampling and monitoring initiatives has been delayed.

### 3.5.1 Current and future level of risk (N4)

#### 3.5.1.1 Current risk (N4)

CCRA2 identified that the risk to the soil resource was severe and increasing, with more action needed to reduce existing pressures on soils and better respond to climate change through proactive conservation of soil resources. We now re-assess that previous analysis in the light of new evidence. However, limitations regarding current soil sampling monitoring relative to the inherent spatial and temporal variability of soil properties and processes act to constrain confidence in knowledge of existing risks, meaning there is a possibility that risk magnitude could be higher than identified.

Climate parameters influencing soils include temperature (notably through its influence on soil temperature and net primary productivity); precipitation and evapotranspiration which influence soil moisture, water leaching etc.; and wind which can interact with specific soil textures. These parameters interact at different scales, and also with other influences such as parent material, topography, fauna, and flora, meaning soils can be complex and vary over small spaces, even at field level. Land use and land management also varies with soil type which over time can cause further variations in soil types.

As identified by CCRA2, there are notable difficulties in distinguishing climate change from other factors, and also differentiating climate change trends from background climate variability (especially in terms of the influence of precipitation). For this reason, evidence for some risks to soil health has no clear consensus, although this can also be related to methodological differences. A further challenge for soils is that the current generation of land surface models used for climate change assessments have limitations regarding the crucial role of biophysical feedbacks in changing soil moisture and soil hydraulic functions (Robinson *et al.*, 2019).

In addition, many risks to soils are the product of climate-related processes acting together with socioeconomic factors to cause soil degradation, notably land use and land management, therefore also contributing to long-term degradation of the land resource. A simple attribution of specific effects to climate as distinct from other factors is therefore probably unrealistic, not least due to the challenges of generalising from limited sample data. Recent soil status assessments reaffirm that generally UK soils are not in a sustainable condition (Natural Resources Wales, 2016; Climate Change Committee, 2018; EA, 2019a; Royal Society, 2020). Soil degradation has occurred from erosion (water and wind), compaction, modification of water-holding properties notably by drainage, loss of soil organic matter (and soil organic carbon SOC), loss or modification to soil biodiversity, imbalance of nutrients, release of legacy contaminants into water bodies, and soil sealing. Climate change potentially could have some benefits for soils through enhanced net primary productivity (from temperature increases and elevated CO<sub>2</sub>) and increased organic matter, but this will also be affected by temperature-related changes in decomposition rates: evidence here remains equivocal as discussed further for Risk N5.

As summarised below, available evidence suggests aggregated climate-related pressures (direct or indirect) cover a significant proportion of the UK soils resource, with major implications for ecosystem services that soils provide. Nevertheless, the sparsity of large-scale soil monitoring data limits our understanding of current trends in climate-related pressures. Natural England's Long-term Monitoring Network (LTMN) is currently the only ongoing long-term sampling programme assessing soils in the UK and this is concentrated on semi-natural habitats in England rather than the broader range of land uses that would include agricultural, afforested or urban environments. This LTMN has recently completed a baseline assessment which provides data on spatial variations in soil properties as a precursor for further work on trend analysis (Natural England, 2017). In Wales, the Glastir Monitoring and Evaluation Programme (GMEP: Emmett *et al.*, 2017) has used 4 indicators of soil quality to summarise progress on land used for agri-environment schemes, finding an improving long-term trend on almost 50% of this land, with 10% a declining trend (remainder not changed).

Regarding soil compaction, recent assessment affirms that this has a serious detrimental effect on soil structure for a significantly large area of the UK, also affecting crop rooting and productivity, decreasing infiltration rates (therefore affecting flood risk and water quality through increased runoff), and increasing N<sub>2</sub>O emissions (Royal Society, 2020). An estimated 3.9 million ha of agricultural land have been identified at risk of compaction in England and Wales, with the risk highest on clay soils during wet periods and for arable land. This large area at risk means that the total cost of compaction has been previously estimated at £472 million/yr (nearly 3 times greater than estimated for erosion) using a methodology based upon dominant soils/land use combinations ('soilscapes') and valuation of final ecosystem goods (Graves *et al.*, 2015). Loss of soil macropores have been identified as especially critical in increasing surface runoff response which climate change may be exacerbating through increased rainfall rates (Alaoui *et al.*, 2018). In Scotland, areas of intrinsic compaction risk have been mapped with a focus on the main agricultural areas (Lilly and Baggaley, 2018), although it is not known with certainty the full extent of compaction within this risk area. Analysis in Wales has indicated that catchment-wide soil structural degradation is estimated to result in a 10 to 20% reduction in soil water storage capacity, and to contribute up to a 10% increase in short term river flow response to rainfall during the field capacity period (Anthony, 2019). In some catchments, soil degradation in combination with changing rainfall patterns (notably greater

intensity) can therefore be a significant factor contributing to increased flood risk, although this will also obviously be influenced by other catchment properties.

In England and Wales, it has been previously estimated that 2.2Mt of soil is eroded each year (EA, 2007). A more recent estimate has suggested a similar soil loss of 2.9Mt/yr with associated productivity losses estimated at ca. £40 million/year, and total costs from decreased soil and water quality at ca.£150 million/year (Graves *et al.*, 2015 using the same soilscales and ecosystem goods methodology referred to above). In Scotland, the total costs of soil erosion by water (including in downstream locations) when extrapolated from 5 case study catchments have been estimated at £31-50 million/yr, with the upper end of the range including drinking water treatment (Rickson *et al.*, 2019). Erosion rates typically vary from <1 to 20 Mg/ha/yr (Defra, 2009), with the higher rates being considerably in excess of soil formation (typically 0.3-1.4Mg/ha/yr) and hence causing severe loss of the soil resource. A recent compilation of UK soil erosion data has suggested that 16% of observations on arable land were greater than the supposedly tolerable rate of 1 t/ha/yr and maximum erosion rates were as high as 91.7 t/ha/yr, although the database probably contains a bias towards locations with a known erosion likelihood (Benaud *et al.*, 2020).

Evidence is increasing that in agricultural areas, degraded soil structure and ineffective artificial drainage may be notable contributors to increased flood risk and poor water quality, although this evidence is mainly from specific catchments rather than a large-scale survey. Analysis in 4 Scottish catchments following the extremely wet winter of 2015/16 by Hallet *et al.* (2016) using a sample of 120 fields found a 30% increase in occurrence of severely degraded topsoils compared to the situation before. Run-off, erosion, and nutrient losses increased by about 10 times in the most degraded parts of the fields (tramlines etc.) and a simple model suggested some agreement between structurally degraded areas and those ranked as being susceptible to topsoil compaction.

Drained and cultivated lowland peatlands are identified as notably vulnerable to climate change, as they currently lose about 1-2cm of soil depth every year due to oxidation and erosion, with the loss of soil carbon reducing soil fertility and contributing ca. 7 MtCO<sub>2</sub>e/yr to UK GHG emissions (Environment Audit Committee, 2016; Office for National Statistics, 2019. Observed increases in rainfall intensity shown by the UKCP18 study of current climate trends imply increased soil erosivity and soil losses to water erosion, as found by analysis of recent data for south-east England (Burt *et al.*, 2016). Increased soil erosion risk is especially present on land uses (notably arable) that involve bare ground at sensitive times of the year unless precautionary management practices are in place.

Implications of current climate change for losses of soil organic carbon are specifically addressed in Risk N5. Again, as identified by CCRA2, the complexity of soils in terms of spatial and temporal variations, notably lagged effects and ongoing adjustments towards an equilibrium with climate, land use and other drivers, mean there continues to be considerable uncertainty at UK scale. Graves *et al.* (2015) estimated the total organic carbon loss in England and Wales to be 5.3 Mt/yr from all drivers and equated this with annual costs of £3.5 million/yr from impacts on agricultural productivity and £566 million/yr from excess carbon emissions (using soilscales and ecosystem goods methodology referred to above).

Regarding the impact of wildfires on soils, evidence suggests damage occurs from hotter, more intense fires that spread heat to the substrate (Belcher *et al.*, 2021). In the UK, fire frequency remains episodic making a climate-related trend difficult to detect but occasional larger fires occur in

dry conditions during spring and summer which can become especially extensive and longer-lasting on peat soils causing substantial soil damage, biodiversity loss and carbon emissions (see Risk N5).

CCRA2 extensively reviewed evidence for the impact of climate change on soil biodiversity and soil composition, including implications for ecosystem functions. The direct and indirect effects of temperature and moisture changes vary across differing soil types and their associated land uses which makes generalisations difficult, but key functional groups, notably the changing status of decomposer, has been identified (Classen *et al.*, 2015). An additional risk factor is the introduction of invasive species with their establishment and spread encouraged by climate change. For example, it has been suggested that introduction of the New Zealand flatworm may have reduced earthworm biomass by 20% (Murchie *et al.*, 2013), with resulting implications for soil structure and functioning because of earthworms' key role as ecosystem engineers. Earthworm presence in agricultural soil has been associated with a 25% increase in crop yield and a 23% increase in above-ground biodiversity (van Groenigen *et al.*, 2015).

Climate change can influence soil microorganisms directly and quite rapidly by altering their growth and activity, but also by indirect effects through plant-soil interactions, but we continue to have limited evidence on these changing feedbacks. Interaction can therefore occur through shifts in plant communities and vegetation (including litter quality and water-use efficiency), which modifies resource availability for soil microorganisms. Similarly, plant growth is also strongly influenced by the soil microbial community that provides nutrients through mineralization of organic matter. The limited evidence on these feedbacks should be a major source of concern because this reciprocal relationship underpins ecosystem function and resilience, hence regulating ecosystem services (including water and soil purification) that then also maintain delivery of other ecosystem services (provisioning and cultural).

Finally, it should be noted that some soils are primarily the products of past industrial activities that have left a legacy in terms of release of unconsolidated material from contaminated land, spoil tips, and mine tailings. These have always been vulnerable to reactivation, especially during extreme weather events, most notably heavy rain. However, the current trend towards increased frequency and magnitude of intense rainfall events (see Chapter 1: Slingo, 2021) indicates a further elevation of risk for this hazard, especially for former mining areas. Recent awareness of this risk has been most pronounced in Wales, where 40 old spoil tips have been assigned to the high-risk category whilst over 9000 contaminated sites have yet to be fully investigated (see Chapter 4: Jaroszweski, Wood and Chapman, 2021 for more details). Heavy rain during early 2020 caused a large landslide on one of these sites at Tylorstown in the Rhondda valley. It is quite likely that other former mining locations throughout the UK also have changing risk profiles due to changing climate factors but at present evidence on this change in risk is rather limited. Around 300,000ha of UK soil are thought to be affected by the legacy of industrial contamination (Environment Audit Committee, 2016).

#### 3.5.1.2 Future risk (N4)

As detailed below, our interpretation of the available evidence suggests that the climate sensitivity of soils together with their current status, which is often in poor condition, would mean that future climate change would significantly increase aggregated risks to soils and their functions or services. This inference is largely based upon extrapolation of current trends and limited modelling and field experiments, which are usually derived from specific soil types or locations, hence confidence

remains low. In addition, our assessment implies that there is the potential for major threshold effects which will become more likely at higher magnitudes of climate change (e.g., +4°C scenarios). It is also important to highlight the expected strong interaction with future change in socioeconomic drivers, notably land use and the continuing effects of atmospheric or other pollutants, although research on these interactions is also limited.

In addition to the expected effects of temperature increases on biological, chemical and physical processes, soils will also be strongly affected by seasonal changes in soil moisture, and for some soil types this may be even more of a critical risk factor. In this context, UKCP18 projections that suggest increasing soil moisture deficits over much of the UK and for most of the year are likely to have profound implications, including changing the relative rate of soil aerobic against anaerobic microbial activity, together with water and nutrient cycling. Increased soil moisture deficits will also affect soil structure through desiccation effects, modification of soil aggregates, and reductions in organic material that also influence water-holding capacity.

In addition, other supporting new evidence provides further information on drought risk. A high-resolution climate model ensemble projects an increased frequency of droughts for much of southern/eastern UK and extreme droughts for southern UK by 2041-2070<sup>8</sup> with a moderate increase in magnitude, whereas for the later 2071-2100 period there are further increases in drought frequency and magnitude, especially for projections of approximately 3°C to 5°C global warming at the end of the century<sup>9</sup> (Spinoni *et al.*, 2018). This analysis suggests drought frequency is likely to increase not only in summer but also other seasons, notably autumn. These drought assessments use a simplified method for evapotranspiration (Hargreaves-Sarmani) which may potentially over-estimate drought magnitude compared to more robust methods such as Penman-Monteith, indicating further research is required to fully investigate these biophysical feedbacks.

UKCP18 is consistent with previous projections in simulating an increased frequency of wetter winters. This has important implications regarding soil wetness risk and the duration for which soils are saturated and at field capacity. This risk, and associated soil compaction risk, are especially prevalent on agricultural land because they constrain field access and workability, and also if livestock are present to increase the soil degradation risk from poaching. As discussed in more detail in section 3.8 (Risk N6), current evidence including updates with UKCP18 suggests that the period of time with saturated soils at field capacity may actually decrease due to the longer continuation of soil moisture deficits in autumn, but there will still be a major at-risk period during winter and extending into spring when inappropriate use could cause significant damage. The role of field drainage systems in modifying this field capacity period into the future remains an important uncertainty, notably because of the lack of data on the full extent and continuing performance of the drains (due to limited maintenance). Specific issues may also be recognised in those low-lying areas where drainage is co-ordinated through Internal Drainage Boards, recognising that these arrangements have a crucial role also in maintaining soil health as well as agricultural productivity. Similarly, changes in drainage conditions in upland areas used for agriculture (including presence of artificial open drains or 'grips') is likely to have an influence on grassland quality and viable stocking rates without incurring soil degradation, but evidence for this remains limited.

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<sup>8</sup> EuroCORDEX regional climate model ensemble with both the RCP4.5 and RCP8.5 concentrations pathways

<sup>9</sup> EuroCORDEX regional climate model with the RCP8.5 concentrations pathway

More research is also required on changes in wetting and drying spell lengths in soils due to changes in climate variability because in addition to the implications for soil structure, these are important for improved understanding of modified physical, chemical and biological processes, including leaching rates, mineralisation and microbial activity.

UKCP18 also indicates increases in rainfall intensity and when this is coincident with periods when soils are most vulnerable (e.g., bare arable soils during planting of crops in autumn or spring), there is therefore an increased risk of soil erosion. Changes in wind-driven soil erosion remain rather uncertain due to limited confidence in wind parameters in climate change projections. In practice, as with many soil-related risks, both wind- and water-driven erosion can be mostly alleviated by good management, and therefore strongly influenced by any shifts in field- and farm-scale planning that are cognisant of the risk factors.

The implications for soils that are used intensively for agriculture and forestry will strongly depend on any adaptation to the changing climate that conserves and rehabilitates soil resources. As highlighted in CCRA2, a continuation of current practices in sensitive locations is very likely to exacerbate future climate change risks due to erosion (wind and water), compaction, and loss of soil biodiversity, as a further continuation of present risks, but with potential threshold effects.

Regarding soil biodiversity, the slower turnover rates, lower nutrient requirement of fungi and their ability to degrade recalcitrant plant litter, means fungi-dominant food webs (as compared to bacteria-dominant webs) are more prevalent in low resource quality soils, which has been used to infer that they would be more resistant to climate change (De Vries *et al.*, 2012). However, this may not be the case. Sayer *et al.* (2017) used experimental site manipulations of temperature and precipitation over 17 years on a species-rich grassland near Buxton (Derbyshire) together with molecular fingerprinting. This analysis, in contrast to shorter-term studies that have reported high resistance of soil fungi to drought, showed substantial losses of fungal taxa in the summer drought treatments, primarily loss of subordinate rather than dominant taxa which were closely related to plant traits. This evidence indicates how climate change could affect soil microbial communities indirectly via changes in plant resources (leaf material, leaf dry matter content and C:N ratios), especially in nutrient-poor systems with slow-growing vegetation similar to the Buxton grassland.

CCRA2 reported on the lack of consensus regarding future changes in soil organic carbon (SOC) and this uncertainty continues (see also N5). Although evidence generally supports a conclusion that warming enhances fluxes to and from the soil, the net balance between gains from primary productivity and losses from decomposition remains more uncertain with large variations between models and single-site experiments (Bradford *et al.*, 2016). UK data was included in a global meta-analysis of multiple site-based experiments by Crowther *et al.* (2016) which suggested that net warming-induced losses would be proportional to the size of the initial soil carbon stock due to the greater potential for accelerated decomposition through temperature sensitivity. This would imply a much greater loss of SOC for higher magnitudes of climate change (including 4°C compared to 2°C scenarios), especially for areas of large carbon stocks as occur in UK peatlands. However, a more recent meta-analysis of experimental data has disputed these findings suggesting that large variations at site level tend to confound a simple interpretation based upon common dominant predictors (van Gestel *et al.*, 2018).

For peat soils, a scenario of 4°C global warming by the end of the century<sup>10</sup> would slightly increase overall blanket peat erosion for N Pennines (Li *et al.*, 2017). Predicted erosion rates were found to decrease at locations that are currently wet and cold, whilst in some warmer and drier locations they increased by > 50% indicating summer desiccation may play an increasing role in future peat erosion for vulnerable areas such as the North Pennines.

CCRA2 also evaluated evidence and uncertainties in dissolved organic carbon (DOC) fluxes from soil, with climate factors acting in combination with DOC release due to declining atmospheric sulphate deposition. Recent work has also investigated combined effects of climate and sulphate emission scenarios for nine major peatland catchments (collectively providing 57% of UK drinking water supply). This showed that changes in soil biophysical processes and reduced river discharge could cause annual DOC concentrations to increase by as much as 53% in the Severn catchment for the highest emissions scenario (UKCP09 A1FI scenario) by 2090, although the Tyne catchment had the highest mean concentrations (Xu *et al.*, 2020). Large increases (by as much as a factor of 1.6) in DOC concentration by the 2090s compared to baseline conditions are projected for autumn and winter, these being the seasons when DOC concentrations are already often high at present and when water treatment works often reach their processing capacity. This work is based upon assumed further decreases in sulphate deposition for Europe, decreasing to 36% of baseline levels by 2030 and 18% by 2090. Regarding causal processes, investigation of drought relationships with DOC has suggested that changing soil microbial processes are the dominant influence (anaerobic to aerobic conditions) and climate change could further alter these relationships in peatlands by causing a vegetation transition towards more drought-tolerant grassland species that produce DOC compositions which are harder to remove by conventional treatment processes (Tang *et al.*, 2013; Ritson *et al.*, 2017).

In addition to discolouration of water, increased DOC flux to water resources has important implications for drinking water treatment because DOC is associated with production of treatment by-products that can have severe human health ramifications (see 'cross-cutting' risks below). Hence, if raw water quality cannot be maintained through improved land management measures (e.g., blocking of artificial drainage) then investment in additional drinking water treatment will therefore likely be necessary by water companies. Water companies are already investing in improved monitoring and online sensors for DOC in treatment plants.

Although new evidence suggests an increased frequency and magnitude of wildfire in the UK due to climate change factors (see Box 3.1: Introduction), the consequences for soils are yet to be fully understood. Nevertheless, available information does suggest that increased wildfire incidence is likely to coincide with vulnerable soils, notably peat and other organic soils, for which long-term damage may occur unless fire is prevented or quickly suppressed. A key risk factor, especially for organic soils, will be the depth of the water table, and which has been lowered in many moorland or fenland locations by artificial drainage channels such that the surface peat deposits are drier in summer and hence more flammable. Projected trends towards drier summers in UKCP18 will produce a tendency to further increase soil moisture deficits and lower water tables in these vulnerable locations adding to the overall wildfire risk. This exacerbated risk may be at least partially

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<sup>10</sup> UKCP09 probabilistic projections with the medium emissions scenario (SRES A1B)



reduced by ensuring soils are in good condition, notably by blocking of artificial drainage channels and restoration of functioning wetland ecosystems including full vegetation cover.

#### 3.5.1.3 Lock-in (N4)

The main lock-in risks are associated with unsustainable land use decisions and continuation of management practices that are a poor match with local soil types, bioclimatic conditions and topography. There is considerable evidence in the wider academic literature (e.g., evaluating agri-environment schemes or uptake of new innovations) to show that land use decisions are often strongly influenced by past decisions and therefore follow a form of path dependency. The legacy of these past decisions can therefore be the dominant factor in continuation of preferred land uses and existing practices, despite the influence of changing government policies, and new incentive schemes. For those locations where land use practices are less suited to the intrinsic soil properties, there is an increased likelihood of further degradation and that rehabilitation of finite soil resources becomes increasingly difficult as climate change increases in magnitude.

#### 3.5.1.4 Thresholds (N4)

There are important potential threshold risks for soils but identifying these in practice is often very difficult due to multiple interacting factors (climate and non-climate). For example, there are potential temperature-related thresholds for accelerated decomposition of soil organic matter which may then exceed inputs from increased primary production. However, in reality, other factors such as moisture availability and CO<sub>2</sub> concentration also have an important role. Similarly, some work has suggested that organic soils, and especially peat, have a critical temperature threshold beyond which they become less viable, as discussed in CCRA2, and these thresholds are typically used in bioclimate envelope models to infer changes in future risk levels. The CCRA3 Thresholds project (Jones *et al.*, 2020) explored such a threshold effect suggesting that a large area of UK peatland could pass such a threshold, especially in a scenario of 4°C global warming<sup>11</sup>, implying large-scale losses of peat soils and habitats.

However, such a conclusion needs to be interpreted with caution. Peat soils can be stable at higher temperatures if also accompanied by wet conditions, as occurs in the hyperoceanic climate regimes of the western UK (and also warmer areas of continental Europe), and indeed carbon sequestration can even increase in such conditions (see risk N5). Hence, the main issue is typically whether the peatland area is in good condition (ecologically and hydrologically), and has not been drained, which provides a rather greater intrinsic natural resilience and capacity to adjust to changing climate conditions. The main inference to be drawn is therefore that if peatland is in good condition, then the likelihood of most of it being resilient against climate change is rather greater in a +2°C world compared to a +4°C world, especially for westerly locations.

Another important example is thresholds related to soil erosion, notably precipitation rates in the context of climate sensitivity. The CCRA3 Thresholds project (Jones *et al.*, 2020) used a methodology for erosion potential based upon a European study using RUSLE (Panagos *et al.*, 2015) and investigated changes based upon a 30mm/day rainfall intensity threshold. Projected soil losses due

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<sup>11</sup> UKCP18 regional projection driven with the RCP8.5 emissions scenario, driven by a global model reaching 2 °C global warming between 2025 and 2034 and 4°C global warming in the 2060s

to heavy rainfall at a UK scale increase from 4.2 Mt/yr at baseline (2001-2010) to 14 Mt/yr for 2°C global warming and 11Mt/yr for 4°C global warming. The apparently anomalous scaling of increases for 2°C and 4°C worlds is a consequence of relative change in rainfall intensity in UK regions with higher or lower arable area based upon the single climate model run utilised (therefore may be expected to vary with different model runs). It is also worth noting that these results also do not account for the likelihood of changes in land use patterns in the UK, including shifts in intensive agriculture to new areas (see Risk N6).

#### 3.5.1.5 Cross-cutting risks and inter-dependencies (N4)

Soils are structurally and compositionally inter-related with terrestrial species and habitats through functioning ecosystems and therefore fundamental for agriculture/forest productivity, carbon storage, water quality and water quantity/availability (including relating to flood and drought risk), structural stability for infrastructure, landscape character and cultural value. Hence, detrimental effects such as through unsustainable land use, pollution, or invasive species can have far-reaching consequences. Drivers and policies influencing land use intensification, such as to increase domestic food production, or increased uptake of unplanned responses through autonomous adaptation (e.g., changes in cultivation practices), can have major ramifications for soil health and in a cross-cutting context for the many ecosystem services that depend on healthy, functioning soils. Cross-sectoral analysis has shown the key role of soils, especially in considering future risks and opportunities for biodiversity, agriculture, forestry and water resources, and furthermore that to neglect to include these interactions will provide misleading information for risk assessment and adaptation responses (Harrison *et al.*, 2016).

Degradation of soils in combination with climate change is likely to lead to severe long-term issues (potentially irreversible) in affected areas. For example, with soil erosion due to poor land management, as triggered by intense rainfall most of the damaging consequences are off-site (Graves *et al.*, 2015) including for water quality (drinking water and bathing water standards), freshwater biodiversity, and GHG emissions. Soil condition and climate-related changes in moisture content also have important implications for infrastructure networks, notably from increased subsidence risk on vulnerable clay soils due to increased soil moisture deficits in summer (Pritchard *et al.*, 2015) or slope destabilisation following heavy rain events (see Chapter 4: Jaroszweski, Wood and Chapman, 2021).

Soil erosion and increased runoff is associated with elevated levels of pollutants in water courses, including coliforms, pesticides, nutrients, and toxic minerals, which have human health implications through drinking water quality and bathing water quality. In addition, increased flux of DOC into water sources has important implications for drinking water treatment because the changing character of the organic material affects its efficiency of removal and its presence can induce reactivity with disinfectants to form by-products such as carcinogenic trihalomethanes (THMs) formed when water is chlorinated to kill pathogens. Recent research using laboratory experiments and monitoring data from five full-scale Scottish drinking water treatment plants has shown significant positive correlations between THM, temperature, and DOC (Valdivia-Garcia *et al.*, 2019). This research also suggested that a 1.8 °C increase in surface water temperature in Scotland by 2050 could cause a 39% increase in THMs.

These relationships between soil degradation, ecosystem services, and human health and well-being have further implications for vulnerable people and communities, not only because they may become more exposed to impacts such as pollution or loss of livelihood, but also because their sensitivity to that exposure is greater. Such indirect effects may exacerbate inequalities, especially in rural areas.

#### 3.5.1.6 Implications of Net Zero (N4)

Soils and especially SOC are crucial to the Net Zero agenda and hence climate-related impacts on SOC will have important implications for achieving the Net Zero goal, especially for peat and other organic soils that have high carbon stocks. The Net Zero agenda is also predicated on major land use changes, including expansion of woodland and bioenergy crops, that in appropriate locations could bring substantial benefits for soil health if also consistent with both present and future climate suitability. By contrast, if such land use changes are poorly planned and implemented then the detrimental effects could be exacerbated by ongoing climate change. A cautionary example here would be the expansion of maize cropping, which is often used for anaerobic digestors and associated reduced GHG emissions, but when planted in inappropriate locations such as steep slopes can accelerate soil erosion and loss of soil nutrients. Similarly, as discussed further for Risk N5, afforestation on some organic or organo-mineral soils incurs the possibility of a loss of SOC through disturbance which could be detrimental to achieving a Net Zero emission target by 2050 (Brown, 2020; Friggens *et al.*, 2020). These examples identify the need for further spatial refinement of Net Zero pathways in terms of sustainability requirements to maintain soil quality in conjunction with the target areas for land use change, in order that incentives do not result in perverse outcomes for soil health (as exemplified by some renewable bioenergy schemes, such as those encouraging maize expansion in locations vulnerable to soil erosion and degradation).

As further discussed in Risk N5, poor implementation of climate change mitigation objectives may have negative consequences for soils. For example, a key pillar in the Net Zero plan is increased afforestation which to avoid good quality agricultural land may become planted on organo-mineral or organic soils. Unless impacts are carefully managed, forestry on such soils can increase erosion and compaction risk and actually result in loss of SOC which acts against the desired climate change mitigation outcome. As recently reported from Wales, organo-mineral soils are also often on steeper slopes and more vulnerable to erosion, whilst also being in close proximity and hydrologically connected to deep peat soils which may further extend the zone of disruption (Berdeni *et al.*, 2020).

Measures that effectively enhance soil health and resilience can therefore be synergistic by increasing the long-term capability of soils to contribute to Net Zero goals in conjunction with the multiple benefits achieved through adaptation for sustaining a broader range of ecosystem services.

#### 3.5.1.7 Inequalities (N4)

No evidence was available to show how societal inequalities may be affected in relation to risks to soils from changing climatic conditions.

## 3.5.1.8 Magnitude scores (N4)

<b>Table 3.11</b> Magnitude scores for risks to soils from changing climatic conditions, including seasonal aridity and wetness					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	Medium	High	High	High	High
	(Medium confidence)	(Low confidence)	(Low confidence)	(low confidence)	(Low confidence)
<b>Northern Ireland</b>	Medium	High	High	High	High
	(Low confidence)	(Low confidence)	(Low confidence)	(low confidence)	(Low confidence)
<b>Scotland</b>	Medium	High	High	High	High
	(medium) confidence	(Low confidence)	(Low confidence)	(low confidence)	(Low confidence)
<b>Wales</b>	Medium	High	High	High	High
	(Medium confidence)	(Low confidence)	(Low confidence)	(low confidence)	(Low confidence)

Notes: Magnitude categories based on expert judgement of existing/expected climate impact on soil biodiversity, properties, and functioning, and associated ecosystem services (except carbon storage: Risk N5). Confidence is constrained by the limited availability of national-scale data. The present risk magnitude is at least MEDIUM and may be higher but there are challenges in attributing soil degradation against multiple risk factors (climate and non-climate).

## 3.5.2 Extent to which current adaptation will manage the risk (N4)

## 3.5.2.1 Effects of current adaptation policy and commitments on current and future risks (N4)

## 3.5.2.1.1 UK wide

As identified above, although evidence remains limited due to lack of comprehensive and updated monitoring, the evidence that is available at present indicates that current trends in soil degradation are in general not being reversed. Notable exceptions can be recognised for some initiatives and locations such as through agri-environment schemes, as described below.

Despite growing recognition of the importance of soils, including for the wide range of ecosystem services they support, there is no single policy dedicated to soil and instead it is covered by a range of international and national agreements, including the legacy of EU policy. Hence, prior to the

transition to new policy arrangements occurring at present, soils were intended to be protected through cross-compliance for agricultural payments and by the UK Forestry Standard's Forests and Soils Guidelines, which identify requirements for good practice, but regulatory enforcement has been limited and primarily based upon penalties for the most severe negative outcomes rather than progress towards positive outcomes as supported by detailed monitoring (Environment Audit Committee, 2016). Agri-environment schemes have provided a more targeted approach and have delivered positive outcomes in some locations. Soil health has also been protected indirectly by measures targeting water quality as driven by the Water Framework Directive.

An important UK-level initiative that has previously provided updated information on soil properties was the Countryside Survey, which was based upon a programme of stratified sampling (by contrast with grid sampling used by the national soil inventories for England and Wales or Scotland). This initiative had added value in providing pooled data and analysis for a wide range of soil series/associations and habitat types across the UK, although the sampling strategy was primarily habitat based. However, the last published version was from 2007. A move towards a streamlined programme with a more limited collection of sample metrics has been proposed, but at present there is no new data available to facilitate comparisons between countries, including standardised sampling protocols.

Some soil types have received more attention than the general pattern, notably peat because of carbon storage and other benefits. The UK Peatland Strategy (IUCN, 2018) sits alongside the existing country level peatland plans (see below) and supports the development of additional or future plans. The strategy aims for 95% (2M ha) of peatland in good condition, under restoration, or being sustainably managed, by 2040, with an interim target of 50% by 2030.

#### 3.5.2.1.2 England

A policy aspiration as reaffirmed by the 25YEP for England is to bring all soils into sustainable condition by 2030. The Environmental Audit Committee (2016) has previously reviewed the existing rules for agricultural cross-compliance that link farm payments to good environmental condition, finding they were not sufficient to support the 2030 ambition to manage England's soil sustainably. In making recommendations for policy improvements, the same Committee report highlighted that in the past, rules were only minimally assessed and crucial elements of soil health, such as structure and biology, were not included, with the inference being that cross-compliance was overly focused on preventing further damage to soil rather than restoration and rehabilitation.

The actions set out for soil health in NAP2 are primarily focused on research and monitoring, consistent with the proposals for improved soil information in the 25YEP. Policy is also in transition towards implementation of the new Agriculture Act 2020 which includes land manager payments based on 'public money for public goods', and explicitly includes good soil management as a target outcome. The proposed Environment Land Management scheme (ELM - see Risk N1 for further details) and Soil Health Index is currently under development to be phased in during 2021-2027, with uptake of ELM a voluntary opt-in scheme linked to specific measures required for individual land managers. Work is therefore underway to develop a healthy soil indicator and a proposed soil monitoring scheme including a revised soil data baseline and the incentivisation of good management practices through ELM. Options around future soil protection to replace CAP cross-compliance regulations are also still under development but may be associated with long-term

targets. At present, however, it is too soon to confirm what these planned policies and actions will be.

Within vulnerable catchments in England, the 'Catchment Sensitive Farming' initiative has required farmers to test soils and apply fertiliser or manure accordingly to improve soil nutrient levels and meet crop needs. The rules require farmers to assess weather and soil conditions to reduce the risk of run-off and soil erosion. More recently, the Farming Rules for Water, introduced in April 2018, stipulate key requirements for all farmers to help protect water and soil resources.

#### 3.5.2.1.3 Northern Ireland

In Northern Ireland, current CAP arrangements are continuing whilst replacement policies are still being developed. The recent development of a Sustainable Agricultural Land Management Strategy recognises the existing unsustainable use of soils and identifies recommendations to address these problems. For example, less than 10% of farmland in Northern Ireland has an up-to-date soil analysis and 64% of soils are not considered to be at optimum pH. The strategy also calls for a "culture of behavioural change created by the provision of personalised information to empower farmers through measuring and managing the performance of their land", also including a central focus on soils. AFBI ran a Representative Soil Sampling Scheme from 2004/05- 2016/17 using 500 fields randomly selected from intensive cattle farms across Northern Ireland and each winter 100 fields were sampled until the work was suspended. In addition, almost 20,000 fields across over 1000 farm businesses were soil sampled in Autumn/Winter 2017/18 by AFBI through the European Exceptional Adjustment Aid (EAA) funded Soil Sampling and Analysis Scheme.

#### 3.5.2.1.4 Scotland

Current CAP arrangements are continuing in the short term in lieu of further policy development for a CAP replacement. SCCAP2 recognises that there are currently insufficient data and metrics to assess soil vulnerability to climate change and policy is now aiming to develop an improved indicator framework for soil health. For this purpose, Neilson *et al.* (2020) identified 13 potential indicators that could be used as a framework to guide regular resampling to update long-term national datasets, but this study also highlighted a critical knowledge gap regarding the dependencies and interdependencies of those indicators, especially for interactions between soil biological diversity and function. Hence, sensitivity of the individual indicators at national scale against climate change threats has not yet been established. However, maps of intrinsic risk for soil erosion and compaction have been developed based upon texture, profile and slope data for the main agricultural areas (Lilly and Baggeley, 2018), identifying the most vulnerable locations. When evaluated against changing climate exposure (rainfall intensity etc.), these maps can provide a basis for identifying where additional adaptation actions, notably through land management, are likely to be necessary, although this currently remains work in progress. For marginal agricultural lands, a framework to assess adaptation options in the context of natural capital has also recently been developed to highlight changing synergies and trade-offs (Pakeman *et al.*, 2018).

The SCCAP2 also highlights the Soil and Nutrient Network and Farm Advisory Strategy as existing initiatives that can facilitate delivery of progress on requirements for sustainable soils. The 'Farming for a Better Climate' initiative also has options for the agricultural sector that aim to link enhanced

farm productivity with improved soil protection and associated reduction of GHG emissions. There is increasing consideration of soils in the planning system (4<sup>th</sup> National Planning Framework) as part of nature-based solutions, but this is currently primarily focused on Net Zero, whilst SEPA has developed 'Delivering One Planet Prosperity' sector plans that provide guidance on soils and off-site impacts on water quality across a range of activities.

Scottish Government has also committed to increase the restoration rate of degraded peatland from the current target of 10 kha/yr to 40kha/yr after 2020, whilst its Climate Change Plan 2018-2032 update states an ambition to restore over 250kha of peatland by 2030. The same updated Climate Change Plan indicates 6kha of degraded peatland were 'restored' in both 2018-19 and 2019-20, which remains below the target level (in total 25 kha of peatland have been rehabilitated since 2012).

#### 3.5.2.1.5 Wales

Target outcomes have been developed to increase the resilience of soils in Wales, and these are reflected in the national adaptation strategy. 'Sustainable Farming and Our Land' (2019) outlines that future farm support post-EU-exit will be based around the principle of sustainability, including that farmers will receive payments for management of habitat, nutrients, and soil health, as also associated with key ecosystem services. Using UKCP18 data, the Welsh Government Soils Policy Evidence Programme (SPEP) and Climate Suitability and Capability Programme (CSCP) initiatives are providing a research framework to consider interactions between land use and soils decisions in terms of the alternative options required to maximise national resources and the further development of land use support schemes, such as Glastir.

With regard to the threat of movement from unconsolidated spoil tips, a Coal Authority safety review is presently underway that will produce a standardised approach for the future inspection and maintenance of all such sites in Wales.

Soil carbon is one of 46 National Indicators used to track success of the Well Being of Future Generations Act and progress towards the UN SDGs. The new Farmer Payment scheme being developed to replace CAP (the Sustainable Farm Scheme) includes preliminary evaluation of the climate resilience of interventions for a range of habitat types. There is also a 5-year National Peatland Action Programme now being implemented to target and coordinate restoration activities.

#### 3.5.2.2 Effects of non-Government adaptation (N4)

As reported in previous CCRA, wide variations in land management practices continue to be an issue for soil outcomes, especially for agriculture. There are some positive examples of local action and collaboration including agri-environment schemes, native woodland restoration and peatland restoration. Water utilities companies and the food and drink industry have provided soil management incentives (e.g., Mark & Spencer's Plan A; Nestle/First Milk initiative) and there are also various accreditation and quality assurance partnership schemes that include good practice for soils (e.g., LEAF; Tried & Tested; Red Tractor; Soil Association organic certification). In Scotland, the Farming with Nature programme developed by the Soil Association has promoted knowledge exchange and innovation regarding improved soil health.

Adaptation tends to be less explicitly referenced in these schemes compared to climate change mitigation but there is an opportunity for enhanced inclusion and outreach through further scheme development and to include explicit adaptation goals for local farmers. This can include guidance referenced to existing practices and exemplars of good management practices, as for example with use of no-till farming (Skaalsveen *et al.*, 2019; Cooper *et al.*, 2021) or the use of cover crops, that can enable erosion and soil carbon losses to be alleviated, with benefits for both climate change adaptation and mitigation when practices are appropriately matched to local contexts (see also section 3.7.3). Similarly, benefits of good management practice have been shown to be effective in some locations for counteracting peat erosion (Li *et al.*, 2017).

Despite these positive examples, the evidence referred to above also indicates that unsustainable land use decisions continue, based upon short-term productivity goals that neglect the wider importance of soils in adapting to climate change. Analysis of agricultural locations that have been associated with severe soil erosion in SE England indicated that most farmers would change land use or management to avert the erosion risk, in this case from winter crops to grassland, although this seems dependent on agri-environment scheme grants and their continued availability in future (Boardman *et al.*, 2017).

#### 3.5.2.3 Barriers preventing adaptation to the risk (N4)

Soils represent a hidden asset and there is a lack of full recognition of the multiple functions and benefits from soil especially when compared against agricultural productivity (Royal Society, 2020). These benefits are unlikely to be fully recognised by many private landowners, due to the time taken to realise these benefits (from improved management), or because benefits are non-market in nature and the link with incomes is indirect and not fully understood. In addition, they have not attracted the same level of NGO support as more charismatic biodiversity. Much of the negative outcomes of poor soil management are also transferred off-site (e.g., through reduced water quality downstream caused by runoff) and hence not directly apparent to the land user: Graves *et al.* (2015) estimated that up to 80% of damage costs occur off-site.

Our assessment finds that, despite recent renewed interest in the importance of soils, there remains a lack of wider understanding of the benefits of improved soil health for ecosystem resilience in a climate change context. Land use decisions (especially in agriculture), as sometimes facilitated by perverse incentives (e.g., maize-biofuels), therefore usually do not recognise the full long-term value of the soil resource, and informal land manager knowledge of indicators of good soil health has been lost. This is compounded by the complexity of soils and the large variations in space and time, including lag effects, so that cause-effect relationships that may be associated with specific management interventions are often difficult to disentangle. This means there is uncertainty around the methods, metrics, and techniques that can be used to deliver objectives for sustainable healthy soils. The problem has been further exacerbated by the lack of investment in comprehensive soil monitoring to help understand changing soil properties and the effectiveness of different management strategies.

#### 3.5.2.4 Adaptation shortfall (N4)

Although soil health is included in all of the latest UK national adaptation programmes there are not yet detailed action plans to integrate and implement these aspirations. Furthermore, throughout the



UK, planning is not yet accompanied by a comprehensive soil monitoring strategy to better understand and monitor progress on climate change adaptation in the context of other drivers, together with the effectiveness of different interventions and land management strategies, both locally and at national scale. Hence, successful implementation of current policy developments will need further refinement to include baseline and target soil property condition statements to explicitly define sustainable outcomes for soil health, as supported by comprehensive monitoring regimes at the scale of farms and their constituent land parcels, and for the uplands. At present, the only soil type to have time-bound plans for restoration and recovery are peat soils, and the emphasis has been on deep peat and primarily climate change mitigation rather than adaptation planning.

Therefore, despite increased government recognition of the need for soils to be returned to a sustainable condition, the accompanying implementation action at national scale are still considered insufficient to manage the future levels of climate change risks down to low magnitude levels. Although assessed with low confidence due to limited evidence on adaptation, knowledge of the underlying processes is adequate enough to indicate an expected increase in the severity of the risk in the absence of further realised actions.

### 3.5.2.5 Adaptation Scores (N4)

<b>Table 3.12</b> Adaptation scores for risks to soils from changing climatic conditions, including seasonal aridity and wetness			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Very Partially* (Low confidence)	Very Partially* (Low confidence)	Very Partially* (Low confidence)	Very Partially* (Low confidence)

\*Most notably for deep peat soils

### 3.5.3 Benefits of further adaptation action in the next five years (N4)

It has been recognised by several of the studies cited above that further progress in addressing this risk requires an integrated land use policy linking agricultural and forestry productivity with measures that improve soil health and resilience based upon good knowledge of the potential of different soil types and their key functions. The basis for such a response can be recognised in current developments such as ELM in England, the Land Use Strategy for Scotland, the SPEP and CSCP initiatives in Wales, and the Sustainable Land Management Strategy for Northern Ireland. However, the evidence also indicates that having a primary objective to bring soils into sustainable condition in the next decade requires that these policy developments should be also expanded to include further integration of adaptation and mitigation strategies based upon long-term planning, including for ambitious land use policies such as woodland expansion and new bioenergy crops, based upon local soil properties. This would also require improved support for land managers in terms of access to benchmarking data and advice how to improve soil health outcomes consistent with improved use of public payments to soil health tracking and outcomes. With greater technical

support to improve soil health, benefits could also be realised through improved connection of land managers back to their soil and therefore encourage more bottom-up adaptation initiatives based on different local contexts.

This assessment has highlighted the need for more comprehensive soil monitoring to help better understand spatial and temporal variability in soil properties and process in the context of both climate and non-climate drivers. For example, complete GPS soil sampling and analysis in fields at 2ha intervals has been suggested for Northern Ireland (Sustainable Agricultural Land Management Strategy) whereas in Scotland, there has been consideration of comprehensive sampling on a per field basis. In conjunction, successful adaptation will require further development of appropriate indicator metrics based upon monitoring data to measure progress and inform policy, define regulatory requirements and engage with land managers and other stakeholders. Although soil quality indicators are often proposed to assess the delivery of soil ecosystem services, more research is required to better understand the most appropriate suite of indicators and to identify baseline and target levels for use in regulation. Indicators also need to be able to be measured regularly and efficiently in the field without recourse to more detailed lab analysis, but this can be difficult because of the need for standardisation and consistency of procedures. For example, for physical properties, six soil indicators have been proposed that have high relevance for assessing soil functions and policy progress: packing density, soil water retention characteristics, aggregate stability, rate of erosion, depth of soil and soil sealing (Constanje *et al.*, 2017). For ecological indicators, high-resolution and molecular tools needed to investigate soil biodiversity and function have only recently been developed, and harmonized static datasets are just emerging, but further development is required to derive time-series data (Guerra *et al.*, 2021).

As further discussed in Risk N6, amongst the prospective suite of land management innovations that may have considerable benefits for soil protection in the next five years is development and increased uptake of precision farming technology, which can also link climate-smart adaptation actions on the ground with the Net Zero agenda. With further advances in climate services, including seasonal forecasting, as applied to agroclimate metrics (or equivalent for other land uses such as forestry), land management practices may be scheduled and targeted to avoid soil degradation at critical times, as notably occurs for soil compaction during wetter periods. Research has shown that avoidance of soil compaction is likely to be a much more effective strategy than approaches that attempt to remediate compaction damage after it has occurred, such as by subsoiling operations (Chamen *et al.*, 2015). Similarly, the advantages of no-till management systems in terms of both climate adaptation and mitigation require further trialling and policy support based upon recent evidence of multiple benefits including prevention of soil erosion, enhanced earthworm activity, and improved water infiltration, in addition to reduced costs and labour requirement (Cooper *et al.*, 2021). However, support for such strategies may require additional spatial targeting to be consistent with local variations in soil properties, hence the added value of integrating with improved soil monitoring.

A particular adaptation challenge can be identified in terms of improved risk management for spoil tips and contaminated land, and this issue requires further emphasis. A variety of engineering solutions may be applied (e.g., improved drainage of spoil heaps to avoid soil saturation) but there is also further scope for use of nature-based solutions such as phytoremediation and tree-planting to

enhance slope stability, although these will take time and they require a more proactive rather than reactive approach.

#### 3.5.3.1 Indicative costs and benefits of additional adaptation (N4)

Research is now increasingly available on the cost effectiveness of different soil protection measures, which can be applied for assessing adaptation actions, although the distinctive properties of UK soils require that analysis is not simply transferred from other countries but is instead developed through a procedure that is consistent with the UK context.

Investments in soil monitoring would seem a low-regret adaptation and a necessary precursor for subsequent improvements. As discussed in more detail for Risk N6, further investment in climate services (seasonal forecasting etc.) for agriculture and forestry, in conjunction with technological advances (e.g., precision agriculture) and improved management practices may have considerable benefits in averting and redressing many of the current negative outcomes for soils.

Economic analysis of soil protection and climate-smart agriculture generally indicates positive economic returns, although financial returns from a farmer's perspective rather than societal perspective may be limited or take longer to accrue and include non-market or off-site benefits (Kuhlman *et al.*, 2010; Watkiss *et al.*, 2019), indicating also the key role of policy support. For individual practices, measures are often highly site-specific, as reflected in large benefit-cost ratios for similar interventions in different places, and evidence on these practices as viable standalone adaptation strategies remains limited and sometimes contradictory depending on assumptions (e.g., relationship with other measures) and context. Posthumus *et al.* (2015), using an ecosystem services valuation approach, found that for soil erosion, use of tramline management, mulching, buffer strips, high-density planting and sediment traps were the most cost-effective control measures, with contour ploughing also cost-effective in some circumstances. However, the study also noted that assessments of effectiveness really need to be made at farm level or field level, because of the wide variation in biophysical and land use contexts, emphasising again the key role of outreach and guidance in stimulating proactive adaptation actions on the ground.

Previous analysis for CCRA1 and CCRA2 (Frontier Economics, 2011; SRUC, 2013) found uptake in the UK farming community and knowledge of the benefits for such measures was relatively low. For example, adaptations analysed by SRUC (2013) (with one exception, for cover crops) generated positive NPVs. These did not require long lead times and had positive ancillary benefits, but the study still identified the challenge would be to encourage farmers to adopt them. All of this suggests that while sustainable soil management approaches have potential for reducing climate impacts, their uptake requires these barriers to be addressed, and may need a combination of awareness and incentives to realise (Watkiss *et al.*, 2019) though there are obvious opportunities to provide additional incentives through revision of the current farm payment schemes. There is considerable work also happening on soil management as linked with Net Zero pathways and it would therefore obviously be beneficial to increasingly link adaptation assessments with that research.

## 3.5.3.2 Overall urgency scores (N4)

<b>Table 3.13</b> Urgency scores for risks to soils from changing climatic conditions, including seasonal aridity and wetness				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Low	Low	Low	Low

While awareness of the threat to soils has increased, current adaptation responses are not yet commensurate with the extent of the risk. Hence, although policies have been developed with ambitious aspiration targets, the actions on the ground, including ongoing monitoring and support for land managers to protect soil health are not yet in place across the UK. Given the potentially very high levels of future risk and absence of a full policy framework to drive the risk down to a low level by 2100, an urgency rating of ‘more action needed’ has been assigned for all nations.

## 3.5.4 Looking ahead (N4)

Increased investment in national-scale soil monitoring programmes including good coverage across different soil types, bioclimate zones, land uses (farmland; forestry; conservation land) and habitats would have considerable benefits for improved awareness and understanding of risks. This should also include improved monitoring of different management interventions linking both adaptation and mitigation goals without sampling bias and designed so as to ensure activities are not ‘leaking’ between sites (i.e., unintended transfer of risks elsewhere). Integrated land use scenario modelling could help ensure no double accounting occurs and interactions between sectors are captured. These improved monitoring requirements have been evaluated by a range of studies (e.g., Constanje *et al.*, 2017; Emmett *et al.*, 2017; Griffiths *et al.*, 2018; Royal Society, 2020) and could also be further extended through citizen science initiatives.

In addition to relationships with land productivity (Risk N6), it would also be extremely useful to have an improved evidence base on the climate-related implications for the wider range of multiple benefits delivered by soils (across different soil types and groups), including to maintain water quality, alleviate flooding at catchment-scale, reduce drought risk, and for priority habitats and species.

### 3.6. Risks and opportunities for natural carbon stores, carbon sequestration and GHG emissions from changing climatic conditions, including temperature change and water scarcity (Risk N5)

- Warming and other climate factors will interact with spatial variations in the intrinsic properties of different carbon stores to influence outcomes in terms of either risk (carbon emissions) or opportunity (carbon sequestration). Implications also extend to emissions from the wider range of biogenic GHGs and hence net balance of GHG emissions
- Risks and opportunities are here assessed together because of similarity in underlying processes, with the outcome varying due to the spatial and temporal interaction of climate parameters (and their magnitude of change) with other biophysical and socioeconomic factors, including land use decisions (or coastal/marine management decisions for 'blue carbon' storage).
- There is only very limited coverage of adaptation planning within carbon and GHG emissions assessments, due largely to limited information and the underlying challenges that climate change uncertainty implies for managing pathways to Net Zero.
- Risks and opportunities for natural carbon stores and net GHG balance are scored as requiring more action, with the magnitude of risk increasing from medium at present to high in future.
- The need for more action is especially urgent given the commitment to reach Net Zero GHG emissions in the coming decades.

This topic presents both risks and opportunities that occur from the effects of a changing climate on carbon stores and GHG emissions, and therefore on the UK commitment to reduce GHG emissions through climate change mitigation. In addition to CO<sub>2</sub> this assessment also includes the two other biogenic GHGs associated with the natural environment, CH<sub>4</sub> and N<sub>2</sub>O, as required to appropriately understand their combined implications in terms of the net contribution to global warming. It also covers the full range of environments: terrestrial, freshwater, coastal and marine. In this assessment we aim to show how addressing risks and maximising potential opportunities are especially associated with better alignment of climate change adaptation and mitigation strategies, which have often followed largely separate policy pathways to present.

As with CCRA2, this topic requires more action, arguably even more so now with the additional UK commitment to reach Net Zero GHG emissions in the next few decades. The magnitude of risk increases from medium at present to high in future, but currently there is only limited inclusion of climate risk assessments within carbon and GHG emissions assessments. Partly this is due to limited information, which also indicates a need for more research investigation, but also because of the underlying challenges that climate change (and other) uncertainty implies for managing and monitoring pathways to Net Zero GHG emissions across both land and sea. Our assessment is mainly based upon expert opinion, due to these constraints on evidence availability, especially for the future projections, but supported by baseline and rate of change estimates where possible.

Regarding interactions with EU-exit and Covid-19, there is limited evidence. EU-exit will have an influence through its relationship with land use patterns, especially for agriculture (e.g., trade agreements; regulatory frameworks), and their impact on soils. For Covid-19 it is too early to infer consequences but there is some evidence that monitoring initiatives have been delayed.

### 3.6.1 Current and future level of risk and opportunity (N5)

#### 3.6.1.1 Current risk and opportunity (N5)

GHG emissions in the land sector typically have the highest uncertainty range in the national GHG inventory due to the high spatial and temporal variability in emissions (or sequestration) relative to point sample data. This is because of large variations in soil type and soil processes, land use management (past and present), and climate. The interaction of these different factors often means that it is difficult to attribute the influence of climate change in isolation. Climate can have a direct effect through changes in temperature and soil moisture but also acts indirectly because it influences land management decisions. The issue is further complicated by changes in atmospheric CO<sub>2</sub> concentrations, which is modifying plant photosynthesis and primary productivity to potentially increase biomass and carbon sequestration, although this is also dependent on interaction with other climate and non-climate parameters (e.g., N availability). Conversely, emissions may occur through microbial soil processes acting on organic matter to release CO<sub>2</sub> or CH<sub>4</sub> depending on presence of aerobic or anaerobic conditions (i.e., soil wetness) and temperature. In addition, N<sub>2</sub>O emissions may occur through nitrification/denitrification processes (also linked to soil moisture levels,) either directly from soils or through aquatic pathways. Land use and land use changes can significantly modify the net GHG balance with forestry and semi-natural land uses typically having higher C sequestration potential and C stocks, whilst agriculture, depending on management practices, may deplete soil C stocks, and significantly increase CH<sub>4</sub> emissions from ruminant livestock and N<sub>2</sub>O emissions from fertiliser application.

CCRA2 evaluated existing evidence regarding changes in soil organic carbon (SOC) due to climate change and noted considerable uncertainty, especially as apparently conflicting results were also associated with different analytical protocols. The general consensus is that intensified land use patterns are usually the dominant factor explaining changes in SOC, where changes are detected, but this is not applicable to upland areas where climate change may be having a more discernible effect, possibly through associated vegetation changes rather than direct soil effects (Barraclough *et al.*, 2015). Further analysis has now become available primarily based upon topsoil analysis. In NE Scotland, no changes were detected in topsoil soil C concentrations resampled in 2017 at 37 sites when compared to samples from several decades previously, despite a changing climate during this time (Lilly *et al.*, 2019). Recent soil samples taken for the Glastir Monitoring and Evaluation Programme (GMEP), between 2012 and 2016 also indicated no change in topsoil carbon for Wales (Emmett *et al.*, 2017; Alison *et al.*, 2019). However, as soil C can change throughout the soil profile, further systematic analysis is required to understand if soil C is being redistributed through the profile and whether this co-varies with other factors (e.g., climate; land use; habitat type; N deposition). The apparent discrepancy in evidence for SOC has wider implications because it makes it difficult to confidently set a baseline for SOC, against which the further effects of climate or land use change could be evaluated (Rollet *et al.*, 2020a, 2020b).

Recent larger scale work may also help to further understand the complex interaction of processes that influence SOC levels in the context of temperature and moisture changes. Analysis of a global soil inventory of measured flux data has found that heterotrophic respiration has increased as a proportion of total soil respiration over recent decades, consistent with evidence from meta-analyses and experiments, indicating increased SOC loss (Bond-Lamberty *et al.*, 2018). In addition, a new theory for the persistence or breakdown of SOC in response to environmental drivers has linked it to functional complexity derived from the interactions between spatial and temporal variation of molecular diversity and composition (Lehmann *et al.*, 2020).

Peatland areas, which contain the largest store of carbon-rich soils, are now the focus for considerable restoration efforts because surveys suggest much of the extent is in degraded condition (most commonly due to past drainage but also due to peat extraction for horticulture and fuel etc.), meaning they act as carbon sources (with potentially quite high emissions) rather than sinks (Evans *et al.*, 2017). Evidence suggests degradation and carbon losses are further exacerbated by runoff during intense rainfall events (Li *et al.*, 2017), in addition to increased oxidation during warmer and drier conditions which cause lowering of the water table, especially on bare peat. At present, we do not have good quantitative evidence on the role of ongoing climate change in net carbon losses from peatlands because of the considerable spatial variability and limited monitoring sites, each of which has their own distinctive settings that challenge simple generalisations.

Similarly, even assuming peatlands are functional and have not degraded to become a carbon source rather than sink, the rate of carbon sequestration in functioning peatlands is quite variable (Evans *et al.*, 2017), depending on environmental conditions including climate which vary spatially and temporally. It should be highlighted here that there is also evidence of very high C sequestration rates ( $>10 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ ) from pristine peatlands in some locations indicating their potential as major carbon sinks (Ratcliffe *et al.*, 2018). These locations are typically associated with a mild wet (hyperoceanic) bioclimate, allowing high primary productivity, as exemplified by Dartmoor where current C sequestration rates are rather higher than measured for the rest of the Holocene, and which also suggest a high natural resilience against present-day climate change (Lunt *et al.*, 2019), although possibly not for higher magnitudes of future climate change.

In forestry management, carbon storage in trees is often estimated through association with the yield classes used in productivity assessments, and as identified in previous CCRA these yield classes will be influenced by climate change (see also Risk N6). A complicating factor in assessing ecosystem-based carbon responses to climate change is the additional fertilisation effect from enriched atmospheric  $\text{CO}_2$  concentrations, which is likely to be further compounded by changes in atmospheric deposition of pollutants (notably N and S). Analysis by Guerreri *et al.* (2020) of the climate,  $\text{CO}_2$ , and atmospheric deposition (N and S) effects on GB tree species through water use efficiency (WUE), growth and C sequestration found a variable pattern that was consistent with the north-south climate gradient, species type and stand age. For Scots pine and oak, a clear relationship of increased WUE was detected with rising temperature and increased  $\text{CO}_2$ , which may alleviate some of the effects of increased water stress and contribute to elevated productivity in northern and western locations. Results were less clear for Sitka spruce, probably due to the greater role of management for this species, and for beech, whilst results for N and S deposition and changes in C sequestration were partially confounded by structural changes during stand development.

Both peatland degradation and tree damage are associated with the effects of deer, which are increasing in numbers in many parts of the UK over recent decades, encouraged by the trend to warmer winters, with implications for carbon stocks in peatlands and woodland. This includes both native species (notably the large numbers of red deer in upland Scotland) and the recent expansion of non-native species (sika, muntjac). Further evidence on the scale of this impact is therefore required.

Climate risks to carbon stores are also manifest through wildfire risk, especially when they occur on carbon-rich organic soils and when they damage major vegetation carbon stocks, notably woodland. It has been estimated that GHG emissions of ~0.6-1.4 MtCO<sub>2</sub>e were released from a six-day wildfire in the Flow Country in 2019 (Ricardo Energy & Environment, 2019). Similarly, the large wildfire on Saddleworth Moor (near Manchester) which burned for 3 weeks in 2018 was measured to have emission rates of CO and CO<sub>2</sub> ranging between 1.07 (0.07–4.69) kg s<sup>-1</sup> and 13.7 (1.73–50.1) kg s<sup>-1</sup>, respectively, similar to what would be expected from a medium sized power station (Graham *et al.*, 2020).

Regarding coastal and marine environments, 'Blue Carbon' represents habitats and species that sequester and store carbon. In addition to the trapping of organic material by vegetation, some plants and animals capture carbon by biological metabolic processes in tissues and shells, which may eventually become marine sediments. Important stocks of blue carbon are found in saltmarsh, maerl beds, kelp forest, and seagrass beds (*Zostera*). In addition, there are substantial carbon stocks in UK offshore shelf sediments that are now being mapped in more detail, although here bottom trawling is apparently the most widespread pressure (Luisetti *et al.*, 2019, Legge *et al.*, 2020). Climate-related pressures on blue carbon resources include temperature increases and ocean acidification (reduced pH from absorption of CO<sub>2</sub>). However, considerable uncertainty exists in the dynamics of blue carbon (Thompson *et al.*, 2017) and present efforts are focussed on producing a baseline assessment of stocks. Blue carbon is not currently included in the UK GHG Inventory and concerns have been expressed that further degradation (including physical disturbance to sediments), as exacerbated by climate change, will release this carbon (or result in carbon not being sequestered) increasing atmospheric CO<sub>2</sub>. Research is currently in progress to assess this degradation risk. Using estimates of UK seagrass cover and recent carbon trading values it has been estimated that the total value of the seagrass standing C stock is between £2.6 million and £5.3 million (Green *et al.*, 2018)

In terms of burial rates associated with coastal or marine habitats, saltmarsh typically has the highest carbon sequestration potential (ca. 100-200 gC/ m<sup>2</sup>) with other habitats also providing significant opportunities notably seagrass meadows (ca. 20-70gC/ m<sup>2</sup>) and kelp forests (ca. 30 gC/m<sup>2</sup>) (e.g., Laffoley and Grimdsitch, 2009; IPCC, 2019). Going beyond generic values, in the most favourable hydrodynamic conditions, some species can locally sustain extremely high sequestration rates: for example, eelgrass rates can exceed 3300 gC/m<sup>2</sup>. However, from the perspective of the CCRA a key issue is that these rates vary strongly based upon environmental conditions, and how they vary with climate change drivers such as sea-level rise, water temperature changes, and acidification remains an important source of uncertainty. For example, analysis of seagrass habitats has reported significant variations in carbon sequestration values and cautioned against assuming values can be transferred from one site to another without incurring significant errors (Green *et al.*, 2018). Kelp forest is a 'donor habitat' rather than a major carbon store by itself, therefore exporting approximately 80% of its production with mobile kelp detritus supporting coastal food webs and



carbon sequestration over potentially a much wide area of sea (Krause-Jensen and Duarte, 2016; Smale *et al.*, 2018; Ortega *et al.*, 2019). As discussed further for Risk N14, there is evidence for changing distributions of kelp species linked to ocean warming which may impact on these inter-relationships.

For salt marsh, as reported in previous CCRAs, the ability of the marsh surface to be able to keep pace with sea level rise is strongly dependent on sediment availability. For many sections of the UK coastline, sediment availability is constrained by coastal protection schemes that aim to limit erosion. For seagrass, our interpretation of the limited evidence suggests that the overall effects of climate change remain uncertain, but most likely are negative. Seagrass meadows grow under conditions of weak to moderate wave exposure, therefore locations experiencing increasing storm intensity will be negatively affected. Seagrass also requires high light availability and therefore increased turbidity of coastal waters that may be associated with heavier precipitation events and transfer of suspended sediments in rivers would have negative consequences. Conversely, it seems likely that seagrass would benefit from continuing ocean acidification (see Risk N14) due to it providing competitive advantages over microalgae. Although kelp forests are more tolerant of wave exposure, they may also be negatively affected if storm intensity increases in exposed locations. Further increases in sea temperature would also probably be negative for kelp, although they may temporarily provide advantages by more strongly affecting other species (e.g., sea urchins) – see further discussion for Risk N14 (section 3.16.1).

Although there are existing activities to map blue carbon resources in UK waters, including by JNCC and other agencies, an important research requirement can therefore be recognised to provide ongoing mapping and monitoring of these habitats (extent and sequestration rates) in order to provide a more robust estimate of the Blue Carbon resource and its variability through time as the climate changes. This should also recognise that C sequestration (and other ecosystem services) will also be affected by the influence of climate change on ecological succession in restored habitats (Boerema *et al.*, 2016).

### 3.6.1.2 Future risk and opportunity (N5)

Our confidence is low in assessing future change due to limited evidence and sometimes conflicting findings. These conflicting results can be due to complex spatial variations in GHG flux relative to local biophysical and land use settings, including the possibility of threshold effects, and differences in analytical methods. Climate warming will interact with spatial variations in aridity (risks to soils and vegetation stocks) and/or wetness (potential opportunities in some regions) to influence outcomes in terms of risk/opportunity in conjunction with land use decisions. These decisions include changes within agriculture (e.g., no-till farming; drainage; use of animal waste; fertiliser application; crop residues), forestry (e.g., tree species; silviculture etc.) and other uses (e.g., muirburn), but also between these land uses as strongly influenced by policies for Net Zero GHG and the impact of climate change on productivity. As discussed in more detail in Risk N6, recent work assessing the implications of changing land capability in different parts of the UK through future projections indicates the potential for significant land use changes in both uplands and lowlands, especially due to modified patterns of soil wetness and drought risk. These indirect effects of climate change will interact with the direct effects of temperature and moisture mediated changes on soil

and vegetation to result in complex outcomes for carbon stocks and GHG emissions, both spatially and temporally. In addition, as described earlier, coastal and marine environments have their own drivers of change, which also imply significant uncertainties in terms of predicting future shifts in carbon and GHGs.

As was found for CCRA2, the future outcome for SOC remains rather uncertain. This is a consequence of difficulties in determining the net balance from the dynamic interaction of climate and non-climate factors on biomass C accumulation through temperature and CO<sub>2</sub> increases compared to increased soil respiration and carbon loss through soil warming. Some recent evidence tends to suggest the outcome will be increased SOC loss. For example, a deep warming experiment on mineral soil found that CO<sub>2</sub> production from all soil depths increased with 4°C warming, with annual soil respiration increasing by 34-37% (Hicks Pries *et al.*, 2017). Whole-soil warming experiments therefore suggest a larger soil respiration response than many in situ experiments (most of which only warm the surface soil) and models, but obviously more research is required to substantiate these findings, and also for organo-mineral and organic soils. At field scale, interactions with soil moisture and expected changes in atmospheric deposition (N, S) on primary productivity will also influence actual outcomes (see also section 3.21.3 for inter-connections between changes in SOC levels and other risks to the natural environment, as well as risks in other chapters). Our interpretation of the evidence is that it is also likely that there will be an increased C flux from soil through dissolved organic carbon (DOC) which may then be released as CO<sub>2</sub>, dependent on seasonal runoff patterns in different catchments around the UK (see Risk N4 for full range of cross-cutting actions that may occur from loss of SOC and associated organic matter: soil quality/productivity, nutrient loss, water quality etc.).

It also seems quite likely that there will be non-linear responses and threshold effects although the details remain elusive. Land surface model simulations driven by climate change on a pathway to 4°C global warming at the end of the century<sup>12</sup> suggest the combined climate and CO<sub>2</sub> fertilisation effect could increase vegetative carbon non-linearly in lowland grassland and woodland ecosystems with spatial variations apparently related to key soil properties (soil moisture and heat capacity) that influence the vegetation response (Boulton *et al.*, 2020).

As highlighted in CCRA2 and discussed in Risk N4 there is evidence for potential increased erosion and oxidisation of degraded peat in future. However, as discussed for current risks, the resilience of peatland is very strongly related to its condition and therefore in some locations, notably wetter hyperoceanic areas, future warming may actually increase C sequestration rates provided that the ecological and hydrological function of the peatland ecosystem has not been compromised.

Future plans to reduce emissions will also be affected by ongoing climate change, and preliminary work is now underway to investigate these interactions. In Wales, the current programme of research to update the Agricultural Land Classification (ALC) has used future land capability projections to explore the implications for the CCC Net Zero plan to plant an additional 152kha of woodland in the country by 2050. Analysis based upon medium-high (RPC6.0) and high (RC8.5) climate scenarios show that the amount of land predicted to remain suitable for sessile oak and Sitka spruce by 2080 is set to decline significantly, mainly due to soil droughtiness constraints (Bell *et al.*,

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<sup>12</sup> The JULES land surface model driven by HadRM3 climate model with the SRES A1B scenario

2020). For the Net Zero planting ambition to be met, it is likely that planting will need to be carried out in areas with significant biophysical constraints that may result in the target yield class (i.e., carbon storage potential) not being fully met and that this may require more flexibility from the agricultural sector to release land that is no longer in the highest grades (Best and Most Versatile (BMV) land: see Risk N6 for further details).

To meet requirements for new afforestation not to occur on prime/BMV agricultural land, it is almost inevitable that some planting will need to occur on organo-mineral or organic soils. Recent work in Scotland and Wales has explored these implications, finding that carbon sequestration is highly variable, with climate an important local factor in addition to tree species, and sometimes (depending on time period of assessment) resulting in net GHG emissions rather than sequestration (Berdini *et al.*, 2020, Brown, 2020; Friggens *et al.*, 2020). In many locations, tree planting is very likely to focus on fast-growing conifers that will require enhanced drainage to become established on these soils (Sitka spruce is the most common species). Improving drainage conditions and associated disturbance involves a soil carbon loss, which may be exacerbated by the shift to warmer and possibly drier conditions in some locations. This carbon loss may be partly alleviated by good management but needs to be better accounted for in future emissions projections under the Net Zero plan. An alternative approach would be to support and enable a much greater proportion of woodland expansion through natural regeneration; native species would be more slower growing than non-native conifers but would not incur the significant carbon loss incurred through soil disturbance and drainage required for the latter to become established on wetter soils (whilst also providing important additional biodiversity benefits).

In addition to climate-related changes in CO<sub>2</sub> emissions, it is very likely that changes will also impact the flux of N<sub>2</sub>O, most notably through interaction of soil moisture and temperature with nitrification/denitrification processes that are acting on organic and inorganic fertilisers. Even in the present climate, process complexity at multiple scales means climate effects are often difficult to decipher therefore future projections remain at an early stage. The changing amounts, proportion and timing of fertiliser application will be key risk factors together with the climate parameters. It is also possible that there will be increased volatilization of NH<sub>3</sub> due to increased future evapotranspiration rates, and changes in denitrification of aquatic NO<sub>3</sub> in streams due to warming, both of which indirectly contribute to N<sub>2</sub>O emissions. These changes may have implications for the default emission factors used in GHG emission inventories and associated assessment of abatement potential.

A further risk to consider is changes in wildfire frequency and/or magnitude, which can affect carbon stocks in both vegetation and soils. Future modelling suggests a substantial future increase in wildfire risk (See Box 3.1) which may have severe implications in peatland areas or for other organic soils which are major C stores.

In addition, in a future scenario where deer numbers are unmanaged and continue to increase, aided by the continuing trend towards warmer winters, it may be inferred that carbon losses due to excessive woodland browsing (notably of young trees) and upland peatland degradation through loss of vegetation in blanket bog and associated habitats are both likely to increase. Further evidence is required to test and quantify the magnitude of this effect.

Regarding 'blue carbon' there is rather limited evidence for assessing future changes in UK stocks at present. However, global assessments and experimental work are consistent in identifying a much greater risk of loss of coastal and marine carbon sequestration at higher magnitudes of climate change as associated with both warmer temperatures and acidification risks for marine organisms (see Risk N14) and sea level rise for coastal habitats (see Risk N17).

### 3.6.1.3 Lock-in (N5)

Land use systems have considerable inertia and path dependency due to underlying sociocultural factors, meaning past preferences, choices, and decisions often have a high influence on present and future decisions. If management decisions continue to be made based upon past climate and other extraneous factors (e.g., commodity markets), then it is likely that there will be further significant GHG emissions that are exacerbated by ongoing and future climate change. Markets and other short-term economic factors, together with new international trade agreements following EU-exit, will be especially influential for agricultural land decisions, and these may act against the optimum strategy for reducing emissions. Land use policies can also inadvertently cause a significant lock-in effect, especially when they reinforce existing cultural positions amongst land managers (e.g., between forestry and agriculture). In addition, increased use of carbon offsets schemes such as in afforestation or peatland restoration without adequate consideration of how target locations will be affected by climate change over future decades also runs the risk of not producing the intended emissions reductions in practice. For degraded peatland areas, the challenges inherent in converting a net carbon source to a sink depend on the scale and extent of degradation, therefore inaction now may potentially lock-in irreversible damage at some sites and is more likely to incur additional ongoing ecosystem service losses and increase later restoration costs, if indeed restoration is possible at the later stage (Watkiss *et al.*, 2019).

### 3.6.1.4 Thresholds (N5)

There are important threshold effects, although these are complex. Most analysis has investigated temperature effects as associated with soils and vegetation C stocks and net ecosystem productivity. For example, as previously reported in CCRA2, Barraclough *et al.* (2015) identified a mean annual temperature relationship for SOC in semi-natural habitats, which was assumed to occur through vegetation feedbacks rather than direct soil-climate effects. The CCC thresholds project also analysed a putative temperature threshold for peatland stability using UKCP18 projections (14.5°C mean temperature for warmest month: Jones *et al.*, 2020). Similarly, as reported in previous CCRA2s, multivariate threshold analysis using bioclimate envelopes suggests considerable loss of blanket bog, as further demonstrated by Ferreto *et al.* (2019) for Scotland whose analysis (using UKCP09 low/med/high emissions scenarios, but climate ensemble model not specified) suggested that "more than half of the carbon currently stored in Scottish blanket bogs will be at risk of loss".

Nevertheless, as discussed above, the net balance of C emissions (and perhaps even more so N<sub>2</sub>O emissions) is related not only to temperature but also to other variables, notably soil moisture, in combination with the condition of the habitat. Upper and lower soil moisture thresholds for soil biological activity have been derived from long-term climate change experiments (e.g., Reinsch *et al.*, 2017). Furthermore, peatland ecosystems have been identified as having multiple steady states with intervening thresholds (Roebroek *et al.*, 2017), and the wide diversity of blanket bog and other

peatland habitats (e.g., species composition; soil organic content; hydrological properties etc.) mean that using general threshold limits may overlook a more diverse response. Our knowledge of the processes does suggest though that it is highly likely though that for a 4°C warming scenario compared to 2°C warming, more of the UK soil carbon stock would be lost due to associated reductions in soil moisture from increased evapotranspiration. However, the magnitude of this difference between scenarios will depend on other factors such as relationships between CO<sub>2</sub> concentration, photosynthesis, respiration, soil moisture and evapotranspiration. C stocks in soils and terrestrial vegetation will also be dependent on land use decisions.

Threshold effects for blue carbon are also highly likely but remain uncertain. Coastal habitats, notably saltmarsh, are strongly influenced by sea-level rise, and at higher magnitudes of climate change the associated sea-level rise has a higher risk of causing severe loss of saltmarsh habitats through erosion and inundation. In addition to the loss of carbon stocks which is of key relevance for Risk N5, this also has very important implications for loss of biodiversity and for other ecosystem services provided by these habitats (see Risk N17). Analysis by Horton *et al.* (2018) using Holocene sedimentary records has indicated that marshes become nine times more likely to retreat than expand when relative sea-level rise rates are  $\geq 7.1$  mm/yr. Using this analysis with future sea level rise projections suggests a major risk of tidal marsh loss for GB, with a >80% probability of a marsh retreat under RCP8.5 by 2100. For higher risk areas of southern and eastern England, an 80% probability of marsh retreat would be achieved by 2040. Conversely, under a low climate change scenario (RCP 2.6) there is a >20% probability of an expansion or relatively stable outcomes for saltmarsh over the next 200 years for Scotland and NW England; however, even under RCP2.6 there remains a >80% probability of marsh retreat beyond 2100 for southern and eastern England.

However, the critical sea-level rise threshold will also vary with the ability of the intertidal zone to migrate inland (i.e., not disrupted by coast protection schemes) and sediment availability (Ladd *et al.*, 2019). Where sediment is available, then the marsh surface can accrete at high rates which may keep pace with all but the highest future sea-level rise projections, more commonly sediment is depleted and marshes therefore are often not even able to cope with existing rates of sea-level rise.

#### 3.6.1.5 Cross-cutting risks and inter-dependencies (N5)

There are many interdependencies, notably with agricultural/forest productivity and with biodiversity (above and below ground in terrestrial systems), and in coastal/marine ecosystems for blue carbon. This shows the need for integrated decision making (policy and regulation) that covers both the land sector and similarly for marine environments, but also linking both the land and marine sectors together more consistently, with coastal environments at the interface. A central component of this integration would be to facilitate closer integration of adaptation and mitigation initiatives, which could otherwise act against each other if developed separately (see Net Zero section below).

In coastal and marine environments, there are interdependencies with management of biodiversity, fisheries, and flooding and erosion. A further significant issue arises from the interdependencies between the land and sea, which are often disrupted due to separate policy frameworks. There is therefore a requirement to ensure more joined-up decision-making across terrestrial and marine policies in the coastal zone, in particular in relation to flooding risks and loss of habitats due to coastal squeeze, which will impact net carbon storage potential.

### 3.6.1.6 Interactions with Net Zero (N5)

There is obviously a direct relationship with Net Zero, but this is especially important regarding climate change implications for the 'Net' component of the GHG balance, and the extent to which carbon sequestration will be able to offset some continuing emissions. At present, climate change projections and their biophysical interaction with carbon stocks and GHGs are not included in forward projections of the UK GHG Inventory (BEIS). This is recognised in the CCC (2020) 6<sup>th</sup> Carbon Budget report and plans are in place to include peatland emissions in future versions of the UK GHG emissions inventory. However, as reported here, there are other habitats and land uses that are highly likely to be impacted by ongoing climate change (both directly and indirectly), including crop production, grasslands, forestry, and coastal/marine environments (not currently included in the emissions inventory) in addition to changes in SOC across the full range of soil types. It is probable that these interactions will have an influence on general emission factors used to scale up habitats and land use coverages to national scale, as shown by existing spatial variations in emissions that can be associated with different bioclimatic zones, although these relationships are yet to be fully investigated.

The evidence presented here strongly indicates that if climate risks and adaptation are not factored into management decisions for the land use sector (at multiple scales, from national policy to individual land parcels), then the Net Zero target will be much more difficult to reach because gains in one area may be counteracted by losses elsewhere. It is also well established, based upon a known temperature sensitivity, that climate change risks to carbon stores and GHG emissions from the land use sector are greater at higher magnitudes of climate change despite uncertainties (due to the considerable spatial and temporal variability of emissions/sequestration rates as related to local contexts), which have resulted in wide-ranging estimates of this positive feedback relationship (Crowther *et al.*, 2016). Furthermore, from a scientific perspective, if the Net Zero target is intended to be commensurate with changes in atmospheric GHG emissions required to achieve a safe future planet for humanity, then the significant risks and opportunities that occur through coastal and marine environments need to be included in the policy process.

### 3.6.1.7 Inequalities (N5)

If the natural environment and land use sector are unable to contribute as much as planned for the Net Zero Target then this will put additional pressure on other sectors which may have ramifications for achieving a fair and equitable transition to Net Zero. It has already been recognised that plans to achieve Net Zero GHG emissions have very important implications regarding societal inequalities, with potentially an excessive burden on the most vulnerable. Therefore, depending on how these plans are further implemented and their resultant interaction with climate factors, there will be both risks and opportunities with regard to addressing those inequalities. The limited available evidence on this topic suggests it is an important topic for further research.

## 3.6.1.8 Magnitude scores (N5)

**Table 3.14** Magnitude scores for risks and opportunities for natural carbon stores, carbon sequestration and GHG emissions from changing climatic conditions, including temperature change and water scarcity

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	High	High	High	High
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Medium	High	High	High	High
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Medium	High	High	High	High
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Medium	High	High	High	High
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

Notes: Magnitude categories based on expert judgement of existing/expected climate impact on carbon stocks and GHG emissions including both from land and coastal/marine environments. This risk has been assessed as increasing from medium (present) to high (under all future projections) due to the climate sensitivity of carbon stores and GHG emissions. Confidence is medium at present (except Northern Ireland which would be low confidence) but only low for the future because of high spatial and temporal variability in the climate relationship, combined with constraints on evidence (limited sample and modelling data). It should be also noted that this assessment combines climate-related information on soil carbon stocks which seem possibly more likely to decrease (although with many uncertainties), terrestrial vegetation carbon stocks (notably in woodland) which are more likely to increase in future, and coastal-marine carbon stocks, with an uncertain net balance.

### 3.6.2 Extent to which current adaptation will manage the risk and opportunity (N5)

#### 3.6.2.1 Effects of current adaptation policy and commitments on current and future risks (N5)

##### 3.6.2.1.1 UK-wide (N5)

In England, this risk is the responsibility of Defra for the UK Government in terms of the risks from climate change to achieving climate change mitigation in the land use sector. For the DAs the responsibility lies in the Scottish Government, Welsh Government, and DAERA (Northern Ireland). The UK Climate Change Act (2008) defines the general policy framework for improving and increasing natural carbon stores, which is then further refined through responsibilities at devolved level, as also now amended by the UK Net Zero target for GHG emissions to be reached by 2050 (with separate devolved targets on 2050 for Wales and 2045 for Scotland). Northern Ireland does not currently have a Climate Act and therefore does not have its own target, although it is implicit in the UK target. This is also especially relevant as Northern Ireland is the only UK country to currently have net emissions from the land use sector, whereas the other countries are a net sink for this sector (although Wales is only marginally a sink and the relative status of countries will change when peatland emissions are fully included in the GHG inventory, as scheduled for 2022).

Although defined as a risk requiring further action in CCRA2, it is still the case across all of the UK that only limited actions to manage the risks from climate change to carbon stores or to maximise the opportunity have been developed. Most of the studies on climate change mitigation, including that feeding into the UK GHG Emissions Inventory and Net Zero GHG emissions pathways, for which the Land Use sector is crucial, do not consider ongoing climate change or interactions with adaptation policy. In addition, as noted above, coastal and marine carbon stocks are not included in the GHG Emissions Inventory (or current Net Zero planning), resulting in a general under-recognition of their importance for contributing to reduced atmospheric GHG emissions and their subsequent added importance for enhancing local resilience.

Across the UK, the woodland expansion and peatland restoration initiatives have tended to have a primary focus on the uplands (with the exception of raised bogs in lowland areas) with to-date a lesser focus on the additional carbon sequestration benefits that could be achieved in lowland agricultural soils that are increasingly vulnerable to loss of SOC through elevated temperatures. The post-CAP plans for each country that are currently in development (see Risk N6 for more details) emphasise the importance of reducing agricultural GHG emissions in line with the Net Zero commitment, whilst also noting the importance of 'climate resilience' but do not identify how emissions reduction strategies will be made more climate-resilient. Hence, the extended scope of integrating climate change adaptation and mitigation initiatives at farm level remains to be fully realised.

##### 3.6.2.1.1.1 Woodland expansion

The importance of woodland expansion in delivering carbon sequestration and Net Zero emissions for the land sector is recognised by all 4 UK nations in national forest strategies and climate change mitigation policies, although target ambitions for new planting vary by country. These policies are relevant to the level of adaptation that may be required but are not adaptation policies in



themselves as tree planting alone does not represent an adaptation to climate risk (unless it is designed to manage that risk, such as through benefits of increasing habitat extent or connectivity, see risk N1 and opportunity N3).

**Box 3.4 – Policies in each UK nation for tree planting to achieve Net Zero**

**England**

The Government's aspiration to increase woodland cover in England to 12% of total land area by 2060, from the 10% cover at present, implies planting rates of at least 5,000 hectares per year. Despite this, annual planting rates from the Forestry Commission are sporadic and show that in no recent years has the annual target been reached.

**Northern Ireland**

The current situation is particularly challenging in Northern Ireland because existing woodland cover is generally lower than the UK average and agriculture has become the largest sectoral source of emissions, actually increasing emissions by 1% from 2014 to 2018. The devolved government in Northern Ireland currently plans to plant 18 million new trees by 2030.

**Wales**

Wales also has a proportionately large agriculture sector and GHG emissions and has only made limited progress on woodland expansion to provide additional carbon sequestration. 'Woodland for Wales' (2018) commits the Welsh Government to deliver at least an additional 2000ha/yr of woodland from 2020 and further measures that would be required to deliver GHG emissions targets.

**Scotland**

Scotland has made most progress on woodland expansion but over recent years this has still been below the ambition that was set by the Land Use Strategy to deliver a sustained programme of 50,000ha of new woodland over a 5-year period from 2016-2021. These planting targets have now been reframed in the context of the 3rd Climate Change Plan, which have seen one recent year meeting the 10,000ha target (2018-19) but the increased target (12000ha) for the following year being narrowly missed. These national planting targets do not take account of where new planting is occurring (notably whether it is on carbon-rich organic or organo-mineral soils), therefore the issues raised above in terms of net carbon balance over different time periods, remain to be resolved, as do underlying barriers regarding woodland on agricultural land. It is recognised in policy commitments that the rate of afforestation needs to increase as highlighted by the considerable expansion of woodland cover identified in the CCC's Net Zero Report and Sixth Carbon Budget advice (CCC, 2020). However, these commitments are defined in terms of new woodland area, and the amount of carbon sequestration obtained will vary significantly dependent on location, including factors such as climate, soil type, previous land use, and tree species.

Although the various national strategies for the forestry sector (see Risk N6 for more details) mention 'resilience' of forest carbon stores, there is no information provided on how robust the projected increases in carbon storage in each country is in terms of the changing climate, as for example on a pathway to 2°C or 4°C global warming. As noted above, this assessment of long-term robustness may be particularly important for woodland planting on organic soils. Based upon the range of present and future climate change risks to woodland (as also described in Risks N1, N6, and N8) this remains an important omission. In addition, the influence of a changing climate on opportunities for enhanced carbon sequestration through spatially-targeted woodland creation has not yet been factored into plans.

#### 3.6.2.1.1.2 Peatland restoration

Peatland restoration activities are increasing across the UK.

##### 3.6.2.1.1.2.1 England

The 25YEP has an objective aiming to restore 'vulnerable peatlands' including an intention 'to create and deliver a new ambitious framework for peat restoration in England', and where restoration is not viable 'new sustainable management measures to make sure that the topsoil is retained for as long as possible and greenhouse gas emissions are reduced'. Defra is currently developing an England Peat Strategy, as committed to in the 25YEP, the release of which is expected in spring 2021. In addition, the Nature for Climate Fund aims to restore 35,000 hectares of England's peatland by 2025. The Lowland Agricultural Peat Task Force will commence work in 2021 with the aim of developing new sustainable management measures for these locations.

##### 3.6.2.1.1.2.2 Northern Ireland

Peatland restoration is being implemented at a range of sites but as yet there is no national strategy or target for delivery.

##### 3.6.2.1.1.2.3 Scotland

The national Peatland Plan, as implemented through the Peatland Action initiative, aims to increase restoration from the current target of 10kha/yr to 40kha/yr after 2020 (and to restore 250kha by 2030), with current restoration activities covering an area exceeding 20kha. In addition, the plan aims to improve the condition and resilience of the wider peatland resource. SCCAP2 has indicators to monitor progress on peatland restoration area and also soil carbon stocks across all soil types. Current data indicates 6kha of degraded peatland were used for restoration activities in both 2018-19 and 2019-20, which remains below target levels (in total 25kha rehabilitated since 2012).

However, as with woodland expansion, there is a lack of evidence that peatland restoration plans are including a robust representation of the long-term ecological and hydrological functioning and resilience of individual restoration sites in the context of a changing climate, including 2°C and 4°C pathways. For example, analysis in Scotland has suggested that much of the restoration to-date has occurred in locations where incentives have attracted interested landowners (especially NGOs) rather than to be targeted at sites where carbon sequestration benefits would be maximised both in the present and future climate (Brown, 2020).

#### 3.6.2.1.1.2.4 Wales

In Wales, the Peatland Policy aims to ensure all areas of peat supporting semi-natural habitat are brought under sustainable management including plans to restore a minimum of 25% (ca. 5,000 ha) of the most modified areas of peatland back to functional peatland ecosystems. This is now being coordinated and monitored through the recently published Peatland Action Programme. The All-Wales Peatland project initiated through the Rural Development Programme also aims to support peatland restoration.

Natural Resources Wales has undertaken a carbon status assessment of the Welsh Government Woodland Estate. This is intended to inform management decisions for restoring and expanding key peatland sites.

#### 3.6.2.1.1.3 Marine and coastal carbon stores

Since CCRA2 there is increased awareness of the importance of marine and coastal C stocks as 'Blue Carbon', including initiatives for restoration (e.g., Natural England £2.5M Seagrass restoration fund) that are being trialled at various sites (e.g., seagrass restoration at Dale Bay, Wales). Improved assessment of carbon storage is also included within Marine Protected Areas initiatives for individual countries. For example, assessment of blue carbon resources in Scotland's inshore MPA network has shown the synergies that exist between reducing climate change risks and net-emissions reductions, and the role of the MPA network in achieving these synergies.

However, specific targeted actions for adaptation relating to marine and coastal C stocks (blue carbon) are in the early stages and changes in these stocks are not currently included in the UK GHG Emissions Inventory (although this is technically possible in terms of UNFCCC Wetlands Guidance). For this reason, potential opportunities for carbon sequestration as one of the multiple benefits that may be obtained from managed coastal realignment are usually not formally included in options appraisals.

In some cases, sectoral policies are in place which may protect C stocks, such as for soils or priority habitats, but they lack a cross-sectoral strategy, meaning they may sometimes be in competition (e.g., forestry expansion and peatland restoration) and not necessarily targeted at the most appropriate locations.

Our assessment is that the lack of evidence on the changing outcomes from interactions between adaptation and mitigation policy means there is considerable uncertainty for this risk/opportunity topic, especially for future risks, which has been a particular problem for climate change mitigation policy (both for the land sector and coastal/marine) as it has sought to show a viable pathway to Net Zero emissions. Hence, there is a strong need for more systematic monitoring and research in the context of the variety of different initiatives to enhance carbon stocks and reduce GHG emissions (i.e., 'what works, where, and when') in order to inform spatially targeted policy and stress testing of mitigation policies against climate change projections and adaptation plans.

### 3.6.2.2 Effects of non-Government adaptation (N5)

Again, there is very limited evidence of adaptation actions that have been integrated with mitigation strategies to protect and enhance current and future carbon stocks, or to maximise net gains for carbon sequestration. However, some land management initiatives, such as those delivering wetland restoration, enhancement of soil organic matter, or native woodland habitat regeneration are very likely to deliver both adaptation and mitigation outcomes through their multiple benefits, although more evidence of this is required.

With regard to soils, investigation of the prospects of achieving the '4 per 1000' soil carbon sequestration initiative (Sousanna *et al.*, 2019) has identified a series of practical barriers based upon resource availability, economic viability and trade-offs with agricultural productivity (Poulton *et al.*, 2018). These barriers are likely to be further accentuated by the concurrent requirements for farmers to adapt to the changing climate, unless improved advice and support is provided. For lowland peats, intensive farming is often highly productive because of the high intrinsic soil quality (unless severely degraded) and although shifts to lower intensity land uses that are more consistent with continued carbon storage are potentially technically feasible, the opportunity cost of loss of market income can be substantial. Therefore, in the context of the current post-CAP transition and reformulation of agricultural support schemes, further policy incentives will be required to address this trade off and recognise the 'public good' of active carbon sequestration.

The Scottish Blue Carbon Forum partnership has become active in promoting and developing a research agenda for improved understanding of blue carbon issues, and uptake of the research into policy, although as yet this has not been included within the adaptation policy agenda.

In Pembrokeshire, Wales, a collaboration between Sky Ocean Rescue, WWF and Swansea University is taking place to restore 20,000m<sup>2</sup> of seagrass, providing decarbonisation benefits, and adaptation benefits to marine wildlife.

### 3.6.2.3 Barriers preventing adaptation (N5)

The societal benefits from carbon storage and avoided emissions of greenhouse gases have been undervalued and the benefits to the land manager are not usually directly apparent, even where associated with soil quality for highly productive land. They have therefore in practice been treated as an externality that runs tangential to primary goals to improve land productivity for food and fibre, or in the uplands to enhance stocks of particular species (notably red grouse) for hunting and shooting.

In some cases, the scientific literature has been critical of exaggerated claims for carbon sequestration from woodland expansion or through the '4 per 1000 initiative' for soils; as these claims have been extrapolated from limited evidence, they do not provide the full picture in terms of the need for a range of robust and varied strategies to successfully match with diverse local contexts. For example, the prominent global assessment by Bastin *et al.* (2019) has been criticised for excluding soil carbon stocks when assessing afforestation potential, and analysis by Poulton *et al.* (2018), referred to above, identifies significant practical barriers to meeting the '4 per 1000' soils target. In addition, work in Scotland and Wales, also referred to above, indicates that at least some

of the woodland planting will be on ‘sub-optimal’ land and therefore may not reach optimal yield classes and the carbon sequestration potential that has been assumed.

Some aspects of existing land management practices can also be a barrier to objectives for enhanced carbon stores and reduced GHG emissions. In addition to challenges for the agricultural sector in reconciling production goals with a reduced GHG footprint, in upland areas the use of land primarily for red grouse shooting and deer stalking needs to reconcile practices (e.g., drainage, burning) that enhance grouse/deer numbers with sustainable habitat and soil conditions that maintain carbon stocks as well as biodiversity and wider ecosystem services to society.

An additional challenge is that restoration of fully functioning ecosystems that maximise carbon sequestration is difficult and requires a long-term strategy. For some habitats, such as seagrass (van Katwijk *et al.*, 2016), evidence also suggests that restoration needs to occur on a large scale to be successful.

Finally, there is a strong need for an integrated approach to GHGs (and other negative emissions) in land management that extends beyond a focus only on CO<sub>2</sub> emissions, therefore including CH<sub>4</sub> and N<sub>2</sub>O in risk assessment to avoid pollution swapping.

#### 3.6.2.4 Adaptation shortfall (N5)

Across the different UK administrations, the evidence available to us suggests there is only very limited coverage of adaptation planning within carbon and GHG emissions assessments and plans. For the future, we assess there to be a significant shortfall in adaptation for England, Wales, Scotland, and Northern Ireland, well below that required to manage risks down to low magnitude level, given the lack of attention being paid to these climate risks in the context of achieving carbon storage and sequestrations goals. Confidence here is low because of limitations of existing evidence for both the land and marine sectors but knowledge of the underlying processes is adequate for us to highlight the reasons for concern. In addition, current plans to reach Net Zero by 2050 (2045 for Scotland) cannot be considered robust in relation to this risk as they do not include stress-testing against a range of climate change projections, especially higher-end scenarios which remain possible either due to socioeconomic factors (delayed global decarbonisation) or exacerbated climate feedbacks.

#### 3.6.2.5 Adaptation Scores (N5)

**Table 3.15** Adaptation Scores for risks and opportunities for natural carbon stores, carbon sequestration and GHG emissions from changing climatic conditions, including temperature change and water scarcity

Are the risks and opportunities going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
No (Low confidence)	No (Low confidence)	No (Low confidence)	No (Low confidence)

### 3.6.3 Benefits of further adaptation action in the next five years (N5)

Achieving Net Zero across the UK assumes major changes in carbon stocks achieved through afforestation and peatland restoration, although the locations for these are not yet specified in policy. As identified above, climate change brings both risks and opportunities for both peatland and woodland, together with other C stocks, and these have a strong spatial dimension. This indicates that a more spatially-targeted strategy for land use change initiatives is highly likely to deliver greater benefits for net GHG balance than an untargeted approach. For example, peatland restoration in areas that will continue to have a cooler, wetter climate and avoiding afforestation with exotic conifers on wetter organic soils (which will require artificial drainage) or afforestation on drier drought-prone soils would help to maximise carbon gains in the required timeframe.

Similarly, improved targeting of appropriate land management schemes based upon their applicability across the wider range of soil types and climate parameters would seem to provide considerable advantages for soil carbon gains. For example, recent research has identified that no-till management systems can provide significant benefits for enhanced soil carbon storage, in addition to other benefits (soil quality, water quality, biodiversity etc.), although with notable spatial variability (partly related to climate factors) compared to conventional tillage (Cooper *et al.*, 2021).

To realise these opportunities and minimise risks will also require improved data on changes in carbon stocks, especially in soils, as achieved through enhanced monitoring across diverse land use, management and climate combinations; carbon certification schemes may be valuable in providing some of these data as associated with the Woodland Carbon Code and Peatland Code. There are also likely to be substantial gains both for adaptation and mitigation through improved agricultural N-use efficiency and avoided air (N<sub>2</sub>O, NH<sub>3</sub>) and water pollution (NO<sub>3</sub>) as recently summarised through indicative analysis for the CCC (2020) Land Use Report.

In addition to enhanced adoption of agroecological approaches (e.g., cover crops; no till; regenerative grazing systems) and improved scheduling of land management activities to avoid disruption to soil carbon stocks, proactive adaptation measures can also take advantage of technological innovations, such as occurring through 'precision farming', to enable better targeting of management activities (Risk N6). Further development of integrated adaptation/mitigation initiatives will also require improved support and outreach for land managers in order to further encourage uptake and knowledge exchange on good management practice. Initiatives such as the Farm Advisory Services for each country and 'Farming for a Better Climate' in Scotland provide pathways to take forward this joint adaptation and mitigation approach.

Benefits would also be achieved by improved assessment and integration of Blue Carbon into initiatives for coasts and marine environments, notably for managed coastal realignment and restoration of intertidal areas and seagrass beds. Increased use of natural adaptation solutions would have co-benefits beyond carbon storage, including alleviation of coastal flooding/erosion risks (see Risk N17) and as a nursery habitat for marine biodiversity (see N14 and N15). Analysis by Luisetti *et al.* (2019), comparing different managements scenarios over the next few decades, has indicated that conservation of coastal and marine habitats is the best option in terms of net carbon storage gains, but that restoration can also be cost-effective although in this case with more complex trade-offs against other policy objectives.

### 3.6.3.1 Indicative costs and benefits additional adaptation (N5)

Evans *et al.* (2017) estimate current annual emissions for English peatlands as around 11mt CO<sub>2</sub>e (other studies given different estimates but around the same order of magnitude). If published non-traded central carbon values and the standard 3.5% discount rate are applied to these, the implied Present Value damage costs up to 2040 are around £13.7bn without further degradation.

Restoration is a low regret action for degraded peatlands (CCC, 2013), with early action having short-term benefits as well as longer-term resilience to climate change. Moreover, early action is desirable given that restoration to a near-natural, fully-functional state can take decades or longer and that restoration costs increase with the degree of degradation faced. There has been some analysis on the costs and benefits of restoring peatlands and enhancing carbon storage (Moxey and Moran, 2014; Bright, 2019, Watkiss *et al.*, 2019), which indicate that restoration is generally worthwhile in most (but not all) cases, for both upland and even lowland peatlands, especially if a broader range of ecosystem services are included (Glenk and Martin-Ortega, 2018). However, these assessments are largely yet to include climate risks and the need for adaptation in achieving these objectives, and also the timing of costs and benefits. In particular, capital investment costs are incurred upfront whilst benefits accumulate more slowly over time (as do any opportunity costs). This makes the choice regarding both the time period over which comparisons are made, and the discount rate by which future costs and benefits are translated to an equivalent Present Value, important. Information does indicate that reliance on voluntary enrolment (rather than regulatory obligations) is likely to limit restoration, because of necessary capital investments but also interactions with (especially) agricultural policy support and market returns (the latter gives rise to high opportunity costs for productive lowland sites) and suggests further action will need incentives.

Economic assessment of carbon storage and GHG issues for other soils, and for the marine sector (wetlands and blue carbon) as a whole remains less available. Forestry is discussed in Risk N6.

### 3.6.3.2 Overall urgency scores (N5)

**Table 3.16** Urgency scores for risks and opportunities for natural carbon stores, carbon sequestration and GHG emissions from changing climatic conditions, including temperature change and water scarcity.

Country	England	Northern Ireland	Scotland	Wales
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Low	Low	Low	Low

We assess that more action is required to integrate adaptation and mitigation policy agendas, given the very large scale of the risk and the absence of integration of adaptation considerations in mitigation strategies aimed at increasing natural carbon storage and sequestration. This includes:

- Stress-testing of proposed measures in Net Zero pathways against the wider range of climate change risks, including the full range of climate projections (2°C world; 4°C world etc.)
- More targeted actions to restore degraded carbon stores, particularly peatlands.
- More strategic approach to land use planning, integrating agriculture and forestry, based upon linking net GHG gains with other multiple benefits.
- More strategic approach in planning and decision-making to integrate the use of land, coast and marine effectively, recognising their interdependencies through development of appropriate policy frameworks.
- More research needed to account for climate change risks to carbon stores in UK GHG Inventory projections (including appraisal of emission factors)
- Better integration of Blue Carbon in adaptation/mitigation planning and reporting
- More investigation of integrated adaptation/mitigation benefits from N-use efficiency in agriculture
- Systematic programme of soil carbon monitoring (including lower soil horizons rather than just topsoil) for diverse land uses, bioclimatic zones, management interventions etc.

### 3.6.4 Looking ahead (N5)

For CCRA4, an integrated programme of research to assess pathways to Net Zero GHGs that are also stress-tested for their robustness against climate change projections (notably UKCP18) would be beneficial. This could collate and evaluate empirical and model data on changes in carbon stocks and GHG fluxes to assess net GHG balance in different contexts. These developments may also be linked with GHG ‘smart inventory’ improvements and an improved evidence of outcomes (and resilience of those outcomes) for a wide range of management options (‘what works, where, and when’) which can be used for spatial targeting of the national adaptation programmes for each UK nation.

## 3.7. Risks to and opportunities for agricultural and forestry productivity from extreme events and changing climatic conditions (including temperature change, water scarcity, wildfire, flooding, coastal erosion, wind) (N6)

- Forestry and agriculture have a close relationship with climate due to its influence on the viability of different crops or livestock, and on land management activities.
- There is good evidence that weather and climate variations affect both utilised land area (forestry and agriculture) and yields, and, in therefore overall productivity. This includes both risks and opportunities through the multifaceted effects of heat and cold, wetness and drought.



- While opportunities from climate change are available (notably due to longer growing seasons), risk magnitude is assessed to increase from medium at present to high in future. This is due to both increased climate exposure (heat stress, drought risk, wetness-related risks) and inherent socioeconomic factors in the land use sector that increase sensitivity and vulnerability, especially for agriculture.
- The assessment identifies limited evidence on adaptation actions and a significant adaptation gap in addressing this risk, especially for agriculture, which also highlights the importance also of continuing research on adaptation strategies.
- The increased level of evidence since CCRA2 indicates an urgency rating of 'More Action Required' because of the significant lead time to develop and implement actions in the land use sector.

This topic covers implications of climate change for the productive capacity of agriculture and forestry, notably for crops, livestock, milk, timber and other fibres. Risks and opportunities for productivity are a key topic because they affect not only land managers and rural communities but also the whole population through changes in domestic food supply and other commodities. In addition, a healthy natural environment requires that production goals are achieved through sustainable practices that do not adversely degrade biodiversity, water, soils, and other ecosystem services, with climate change having important implications for achieving that sustainable balance.

At national scale, productivity is an outcome of the utilised land area for different produce and their unit value (yield). We have good evidence that weather and climate variations affect both the utilised land area and yields, and hence productivity, and this includes both risks and opportunities through the multiple varying effects of heat and cold, wetness and drought. As with other aspects of the natural environment, the relationship between climate and agriculture or forestry is mediated through key bioclimate parameters such as the growing season and associated plant phenology effects, soil moisture variations, frost frequency, and wind exposure. Variations in solar radiation (i.e., sunshine hours) are also a key factor, especially at crucial times of year such as spring and early summer for cereals, and this can show considerable inter-annual variations. These parameters determine the viability and hence overall productivity of different land uses, and, in addition to longer-term trends, vary from year to year, sometimes accompanied by extreme events such as drought, heatwave, or flooding. Humidity can also be an influencing risk factor, as notably in terms of thermal humidity risk for livestock and the incidence of specific pathogens (see Risk N7 and Risk N8).

Distinguishing longer-term trends in productivity due to climate change is more difficult, due to the complexity of interactions, both in biophysical terms, and with socioeconomic factors. During the latter part of the 20<sup>th</sup> century, major gains in productivity were achieved through advances in technology and associated use of genetics in breeding and selection, especially for crops, although this upward trend has been less evident in the 21<sup>st</sup> century to-date. In addition, incremental changes such as the general increase in temperature have been interrupted by sporadic extreme events or combination of events, which have disrupted some types of production, typically those with more intensive requirements (notably arable or horticulture, but sometimes also types of livestock farming).

Nevertheless, there is clear evidence that climate change is modifying the productive capacity and will continue to do so in future, with a close relationship to the magnitude of climate change. In land use planning, the varying capability and flexibility of land areas for different potential uses is a key strategic tool to help maximise and protect land resources, as defined using the interaction of climate with other biophysical criteria, notably soils and topography. This provides the basis for national land capability classification systems: Agricultural Land Classification (ALC) in England, Wales and Northern Ireland; Land Capability for Agriculture (LCA) in Scotland. Grading of land therefore defines the most productive and versatile land: Best and Most Versatile Land (BMV) in ALC and Prime Agricultural Land in LCA. As described below, analysis of both classification systems shows important geographic variations in land resources in recent decades and especially in the future when drought risk is inferred to become a much more significant factor, and hence the availability of irrigation water is very likely to become an increasing concern. As noted above, in addition to these changing biophysical factors which define the potential productive land use, actual production outcomes will be strongly influenced by changing socioeconomic factors such as market prices, local traditions or land manager preferences, and policy drivers (e.g., incentives; regulations etc.).

As with previous CCRA2s, this assessment recognises that in addition to finite land resources, productivity is also dependent on interactions with healthy soils, water, and biodiversity, hence we aim to evaluate risks/opportunities in the context of sustainable production systems, including implications for both the quantity and quality of produce.

Although some opportunities are available, risk is evaluated to increase from medium at present to high in future, and with a significant adaptation gap in addressing this risk, especially for agriculture. Since CCRA2, more evidence has become available on this topic. This new evidence in combination with that used for the previous assessment suggest that the urgency rating should now be 'More Action Required' because of the significant lead time to develop and implement actions in the land use sector. However, important knowledge gaps also remain which highlight the importance also of continuing research on adaptation strategies.

EU-exit will also have an important influence on this risk topic although, as both trade agreements and post-EU-exit land use policy are currently in flux, it is not possible to identify with any certainty how this additional factor will modify both risks and opportunities. Covid-19 is an additional factor that may also modify expected outcomes but at present there is very little evidence on how much an influence this will be for overall productivity.

### 3.7.1 Current and future level of risk and opportunity (N6)

This section is structured through firstly providing an assessment of key climate (and non-climate) factors in terms of general exposure and sensitivity, including also how this is related to land quality through capability and suitability criteria. Then a more specific assessment of the evidence for specific sectors is provided in terms of consequences for production.

### 3.7.1.1 Current risk and opportunity (N6)

#### 3.7.1.1.1 Climate exposure and sensitivity

The influence of climate change can be considered both in terms of incremental adjustments to long-term trends, and the risks from changing extreme events. In terms of the primary bioclimate factors that are used in land classification, the average length of the annual growing season has increased (ca. 15-35 days for grass since 1961-90) which may be identified as an opportunity. Also, the intensity and speed of the growing season has increased: in the most recent decade, annual average growing degree days were 15% higher than the 1961–1990 average and 5% higher than the 1981-2010 average with a clear upward trend over the last 60 years (Kendon *et al.*, 2020). This latter trend may be both an opportunity and risk (depending on the crop and its thermal requirements) through its modification of plant phenology. Bioclimate data for changes in the seasonal moisture balance show a more complex pattern due to the greater influence of shorter-term variability (interannual and interdecadal) but in terms of longer-term trends some important eastern agricultural areas have experienced increased soil moisture deficits, whereas some western districts have been affected by wetter winter conditions (Keay *et al.*, 2014; Brown, 2017), with variable effects in autumn and spring. As discussed below, the influence of extreme events (e.g., drought; flooding and waterlogging; heat stress; cold spells) is evident in specific years and in locations more exposed and sensitive to these extremes but detecting changes in these extremes remains difficult, especially for precipitation-related events due to large interannual variability.

Yields and national productivity (as summarised in annual statistics provided by Defra, the Forestry Commission, and the DAs) are difficult to attribute against climate-related trends due to other agronomic and forestry factors. Nevertheless, climate sensitivity is particularly shown by specific years when productivity was strongly affected. For UK average wheat yields, the extremely poor year of 2012 (6.8t/ha) has been highlighted in previous CCRA, but in more recent years although the 5-year average 2016-2020 was 8.4t/ha, both 2018 (7.8t/ha) which featured a hot dry summer and 2020 (7t/ha) which had a very wet winter and dry spring, have been marked by significant yield losses. By contrast, 2015 and 2019 had above average UK wheat yields, showing the considerable inter-annual volatility. UK barley yields (combining winter and spring varieties) also decreased by 9.1% from 2019 to 2020 but as there was a significant increase in spring barley production area following the wet winter in 2020, meaning the combined result was a 38% increase in spring barley production. In comparison, the total UK wheat production for 2020 decreased by 40% compared with 2019. For other crops, after the hot dry summer of 2018, carrot yields were reported down 25-30% and onion yields down 40% on a normal year whilst potato yields were down on average 20% in England and Wales (Climate Coalition, 2019). These figures also show that the magnitude of risk/opportunity also varies dependent on species (and also variety/cultivar) and their individual sensitivities to climate parameters. In addition, yield impacts also vary with site location and management; for example, on heavier soils, higher water retention capability typically means that yields are less adversely affected by drought but conversely these locations are usually more negatively affected when seasonal conditions are wetter than average.

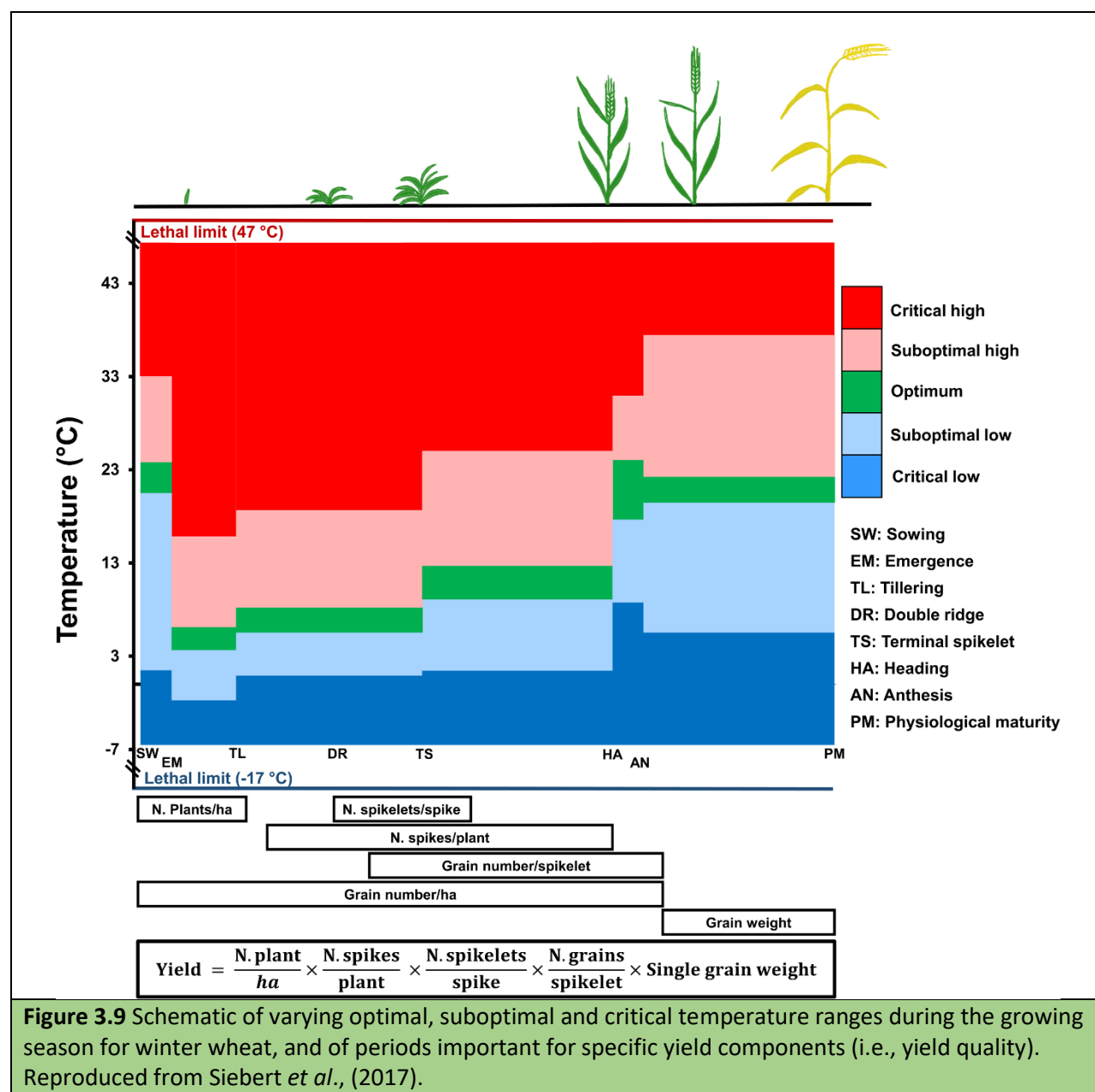
The impact of anomalous weather conditions on agricultural production is also being shown more clearly across Europe. This evidence has relevance to the UK because in some cases the impact of

such extreme conditions is indicative of the changing risks for UK production too, even if not manifest yet. In France in 2016 (most notably in NE France), an unforeseen and unprecedented severe wheat yield loss occurred which has been shown to be the consequence of a new type of compound extreme event combining abnormally warm temperatures in late autumn and abnormally wet conditions in the following spring, with these types of events expected to become more frequent in future (Ben-Ari *et al.*, 2018).

New evidence provides firmer support for inferences on climate change sensitivity made in CCRA2, although challenges in interpretation still remain. Regarding temperature changes, as noted above there is clear evidence for changes in growing seasons and phenology for many crops. Observed temperature changes also show a decline in spring frost frequency and this has also been associated with an impact on some crops, such as for blackcurrant yields (CCC, 2018b). However, relationships are typically more complex than may be initially assumed: seasonal advancement of plant phenology has been shown in wheat to vary with the selection of different cultivars (Rezaei *et al.*, 2018), and there are important interactions with vernalisation in some plants (see below). Furthermore, temperature may not be the dominant influence for some crops: for example, field data have shown a greater sensitivity of spring barley to precipitation rather than temperature variations during the growing season in Scotland (Cammarano *et al.*, 2019). In addition, recent decades have seen a trend towards increased solar radiation for some areas of the UK during the growing season (see Chapter 1: Slingo, 2021); it is likely that this has also contributed towards productivity changes, although evidence is limited and interannual variability has also continued to be large.

Regarding water-related risks, the wide variety of UK geographies in which agriculture occurs means that climate-related risks can include both the effects of too little water (water scarcity; additional effects of drought; and restrictions on the right to abstract water) and the effects of too much water (excess soil moisture restricting aeration and plant growth; waterlogging and flood inundation affecting access to land and its workability and trafficability). As noted above, these risks are currently changing due to shifting patterns of rainfall distribution and resultant seasonal soil moisture variability. We can then infer that the inherent climate sensitivity means that water-related risks will be further modified under ongoing climate change with important implications for land use decisions and national productivity. For outdoor irrigation, field crops currently account for 42% of direct abstraction for agriculture whilst a further 40% is used for drinking water for livestock for which private water supplies are particularly important (79% of requirements for dairy cattle and >90% for pigs, sheep and poultry) (Hess *et al.*, 2020).

When comparing the relative influence of different climatic factors, indicators can provide a simplifying mechanism to compare different influences. For example, analysis comparing different extreme weather indices for 1980-2010 for wheat yield at global scale has included results for the UK (Zampieri *et al.*, 2017). This work found water stress is currently a more dominant factor than heat stress for the main wheat producing areas of southern and eastern England, but also that excess wetness is currently a greater risk factor for much of the UK especially in the north. However, these analytics have been criticised by others as over-simplistic (e.g., Siebert *et al.*, 2017) due to the varying interacting effects of climate parameters across the growing season which even for temperature are complex (Figure 3.9) and may also vary between cultivars.



Climate sensitivity therefore seems a key issue both for different cultivars and different crops. As cultivars have been developed and matched to specific conditions, changes in agroclimatic parameters and frequency of extreme events requires a shift in cultivar choice and new crop breeding programs (Mäkinen *et al.*, 2018). Nevertheless, evidence from Europe suggests current utilisation of available cultivars for wheat remains limited, which constrains resilience and adaptability (Kahiluoto *et al.*, 2019).

### 3.7.1.1.2 Arable and horticulture crops

As identified in CCRA2, and further shown by the updated observed climate data provided by UKCP18, frost days have reduced in frequency across the UK, and this provides benefits for both arable agriculture and horticulture, through reduced incidence of frost damage for vulnerable crops. However, this general warming pattern also has a negative aspect because many tree species and

other crops need an effective vernalisation period of cold weather to produce a good crop every year. Minimum temperature thresholds vary according to species and cultivar, typically with a period of low temperatures needed to induce dormancy in early winter and also a further period of low temperature for dormancy release. Recent work on vernalisation in oil seed rape has suggested that changes in early winter temperatures may actually be the dominant influence (Brown *et al.*, 2019) but further work is required to ascertain the full implications of changes in minimum temperatures.

This reduced vernalisation effect is probably the main impact of climate change for UK soft fruit production at present, most of which is now under plastic (or other) protection, although a comprehensive large-scale sensitivity analysis for this sector is not currently available. However, for horticulture in general, produce quality is a primary issue and from a growers' perspective this means that pests and diseases are often seen as the dominant concern (see Risk N7), potentially in combination with water-related stresses (see survey results in Webster *et al.*, 2017). Concerns regarding produce quality are also related to high quality specifications demanded by major retailers as an assumed response to customer demand for unblemished food products. Quality issues also mean that increased irrigation needs are also a concern, especially in vulnerable crops such as Brassica that need consistent soil moisture, although this may be partly alleviated by increased use of covered systems (polytunnels etc.). In addition, for some crops, reduced times to reach maturity may be providing new opportunities for increased production by enabling multiple crops in a year, such as for lettuce and an increasing variety of baby leaf and salad crops (Armstrong, 2016).

Some crops or livestock-related produce are especially important for specific areas of the UK, including for non-food produce. For example, spring barley is the most important crop (by areal extent) in Scotland, with a high proportion of farm output used for malting barley (proportions vary from year to year due to the high-quality specifications for malting); most of the remaining output, usually lesser quality, is used for animal feed. In 2018, malt barley supply to Scotland's distilling and brewing sectors was impacted by both quality and yield issues due to drought, as noted by sector briefing reports. The drought also caused disruption due to low flow and higher water temperatures impacting fermentation, cooling and overall whisky quality (Fennell *et al.*, 2020), and at some distilleries production was halted for several weeks, these factors combining to have a significant effect (not presently unquantified) on one of Scotland's major export industries.

Hops are another crop with high importance for the drink industry and specific UK locations. Analysis of yields from hop cones based upon different types of weather modes (dry-cool, dry-hot, wet-cool and wet-hot) has shown longer and more severe drought and heat wave concurrences have increased more frequently than shorter concurrences with hot dry conditions especially associated with yield loss, including for major hop-growing regions such as Kent (SE England) (Potopová *et al.*, 2020).

Climate sensitivity is apparent not only for gross crop yields but also specific yields which represent the quality of produce, and which can be particularly important for food production. Regression analysis of wheat quality metrics that are especially used in bread production (specific weight; Hagberg Falling Number (HFN) as a measure of milling flour quality; and protein content) have found strong associations with weather conditions in preceding months (Pope *et al.*, 2019). Monthly sensitivity results depend on choice of metric but rainfall patterns in October, January, June and August appear especially important. Specific weight and HFN are strongly linked to summer rainfall,

with drier than normal conditions associated with increases in these metrics. Protein content appears to be sensitive to early frosts, late summer temperature maxima, and general conditions in December. However, Cammarano *et al.* (2019) found no discernible influence of yearly rainfall variations on malt barley quality at a specific site in Scotland. As already highlighted, fruit and vegetables also have known sensitivity to varying monthly and seasonal conditions, but again clear long-term climate-related trends are difficult to detect. This indicates the need for further research, including different crops and varieties, and metrics, including the wider implications of production shortfalls for domestic food supply (see 'Cross-cutting Risks' covered in section 3.7.1.5).

Although drought conditions have been less frequent in recent years (2018 being an exception), underlying exposure is increasingly evident. The UNSEEN methodology (see Chapter 1: Slingo, 2021) has been used to derive evidence that even within current climate conditions the entire UK wheat production area could be negatively affected by large-scale summer drought conditions in a single year, and because much of the current wheat production is concentrated in southern and eastern England, then when droughts do occur, they usually affect more than ~50% of the UK wheat cropping area as one contiguous cluster in those regions (Pope *et al.*, 2019).

Water availability for irrigation use is an important requirement for drier (predominantly eastern) locations of the UK to produce high-value crops of good quality (Hess *et al.*, 2020). Although the agriculture sector overall takes a small proportion of water supply, in some locations and catchments this is much higher and the seasonal water demand usually occurs at the driest time of year. Due to both increased soil moisture deficits and variability in summer rainfall, and demand for more water to maintain or improve the quality of produce, there are increased pressures for supplemental irrigation. These additional demands on water resources are most pronounced in water-stressed regions such as southern and eastern England, but have now extended to other regions, including eastern Scotland and eastern Wales, especially during drier summers, meaning the distinction between rain-fed and irrigation-fed areas has become less clear.

#### 3.7.1.1.3 Grassland and Livestock Production

In terms of evaluating grass as a crop, modelling of European-scale changes in grassland productivity for 1961-2010 has shown an increase of potential annual grassland production (over 3% per decade) of which 97% is attributed to increased CO<sub>2</sub> levels with 15% attributed to nitrogen deposition/fertilization and only a very small fraction to climate parameters (Chang *et al.*, 2015). This large-scale analysis showed that grassland productivity was higher in western regions of the UK, which facilitates higher livestock numbers in these locations. However, other management factors beyond the role of nitrogen fertilisation (which is included in the Chang *et al.* 2015 study through a rather simple parametrization scheme) play a role, therefore attribution of productivity to different factors may not be necessarily representative of all areas of the UK.

Regarding national-scale livestock production, other factors (notably markets and policy) tend to dominate at present. Livestock farming usually occurs in wetter areas of the UK which also typically experience more interannual seasonal variability, therefore this type of land use is typically more adaptable to changing conditions (although as discussed below, we know there are limits to this current adaptive capacity). As reported in CCRA2, at present only small, localised, effects on milk production have been noted, and in more marginal areas it is often the influence of cold weather in

winter and spring that can be the main limitation on grass production, which are most manifest during more extreme conditions in particular years. High temperatures in combination with intense solar radiation can cause heat stress resulting in a decrease in both forage intake (Hill and Wall, 2017) and production outputs (Hill and Wall, 2017; Van Laer *et al.*, 2015). In housed livestock systems, temperature events that are beyond the capacity of the ventilation system can result in increased energy and water use and an increased risk of disease (Skuce *et al.*, 2013). Also, livestock health (Amundson *et al.*, 2006) and welfare (Van Laer *et al.*, 2014) can be negatively impacted.

In addition to affecting availability for livestock fodder and bedding, variations in straw production can have a negative impact on the livestock sector, with impacts extending to following years. This occurred in 2017-18, including the effects of drought in many locations during summer 2018, with reduced availability and quality of straw causing farmers to source straw from further distances and at increased cost, and with the EU relaxing regulations to allow additional forage areas (Bell *et al.*, 2018; Salmoral *et al.*, 2020). During the same period, arable farmers had to plough in straw to complete autumn sowing causing increased prices, although price increases may also have been affected by increased use in bio-energy production and increased demand due to concerns over animal welfare (Bell *et al.*, 2018).

#### 3.7.1.1.4 Forestry

Similar inferences regarding both climate-related risk and opportunity may be derived for national-level productivity for the forestry sector, although rather more of the sector has a broader emphasis on multifunctionality rather than simple output measures such as timber production (productivity is also associated with other important functions such as carbon sequestration – see Risk N5). As reported by previous CCRA, although there is evidence of enhanced tree growth both from the UK and more widely across Europe, attribution of this to direct climate factors, notably temperature increase, is not conclusively established, due to concurrent increases in CO<sub>2</sub> fertilisation and N deposition (Lindner *et al.*, 2014). Forestry production may also be exposed to sporadic extreme events, notably from windthrow exposure during severe storms and tree mortality or loss of function due to droughts, but evidence remains limited as to whether these have an influence beyond local-scale effects. Hence, it is possible that the largest climate change related influence at present, at least for some species that are important for production purposes, is pests and pathogens (Risk N8); the relative influence of different risk factors is confounded as stress from one risk (e.g., drought) can then increase susceptibility to another risk (e.g., pests and diseases). This combination of risk factors therefore typically acts to limit our confidence in the attribution of individual factors in the absence of large-scale multivariate analysis.

#### 3.7.1.1.5 Flooding, Coastal Erosion and Wildfire Risks

Flood risk is a key hazard that impacts on land use decisions. Over 90,000ha of the best quality land (BMV/LCA) in the UK is at risk of coastal flooding and over 400,000 ha of this land is at risk of fluvial flooding, with significant geographic variations (based upon a 1 in 75-year event: Sayers *et al.*, 2020). A significant proportion of this land has been flooded in recent years, notably from fluvial flooding and especially on alluvial land on the floodplains of major rivers such as the Severn, Trent, Tay, Tweed, Tywi (Towi), Clwyd, and Lagan. By contrast, although still a continuing hazard, amounts of land lost to coastal erosion remain relatively small on an annual basis, although this land is of course



lost permanently, whereas flooded land may be eventually reclaimed and still be used, albeit often through a different use than originally intended. In England, coastal erosion of BMV land for 2005-2025 has been calculated at 74ha using a central estimate (50% confidence level) with an upper estimate of 98 ha (5% confidence level) based upon extrapolation of erosion rates through the National Coastal Erosion Risk Mapping (NCERM) project (Jacobs, 2018). Equivalent figures for other areas of the UK are thought to be lower but remain to be confirmed.

Available evidence suggests that wildfire may be an under-recognised risk with some research suggesting an increase in higher magnitude events when meteorological conditions are conducive (i.e., drier conditions often accompanied by warmer weather), although these conditions remain very episodic meaning trends are difficult to establish [see Box 3.1: Introduction]. There is currently more emphasis on this risk factor for forestry as compared to agricultural land but incidence data show both are at risk (Belcher *et al.*, 2021), although at present the risk magnitude is of high local importance rather than being a factor for overall national production levels in agriculture or forestry.

One major insurance firm (NFU Mutual) has reported that farm fire costs during the dry Summer 2018 for the UK were nearly £32m, an increase of 137% on 2017 with the overall costs of claims for farm fires over the harvest period up by 21% at £5.5m (Ecosulis and Farmlytics, 2019). Anecdotal reports from 2020 have suggested that harvesting during heatwave conditions has incurred a significantly elevated risk on stony ground due to generation of sparks, although quantitative data showing the relationship to actual wildfire events is yet to be produced. Further work is therefore required to show if there is a longer-term trend towards increasing wildfire events on agricultural land.

An important factor to consider is that extreme events often affect not only that year's agricultural production but also have implications, which can then affect following years. For example, planned winter crops may need to be abandoned and replaced by spring-sown crops if conditions allow, or sometimes an enforced fallow year may be required to re-establish favourable agronomic conditions.

Regarding the externalities from production activities, the combination of increased heavy rainfall and prevalence of agricultural practices that result in large areas of bare ground at critical periods (notably autumn) has been associated with severe soil erosion in some locations (Boardman *et al.*, 2017; Rickson *et al.*, 2019), as discussed further for Risk N4. Attribution between climate and management pressures is difficult and very likely to be spatially variable due to local factors, including an increased risk on steeper slopes. In addition, risks of soil structural degradation, notably from compaction, have climate-related and management components (i.e., trafficability and livestock access constraints on wetter soils) with evidence suggesting degradation has become widespread in some locations, notably on arable land (Lilly *et al.*, 2018; Royal Society, 2020; see also Risk N4).

### 3.7.1.2 Future risk and opportunity (N6)

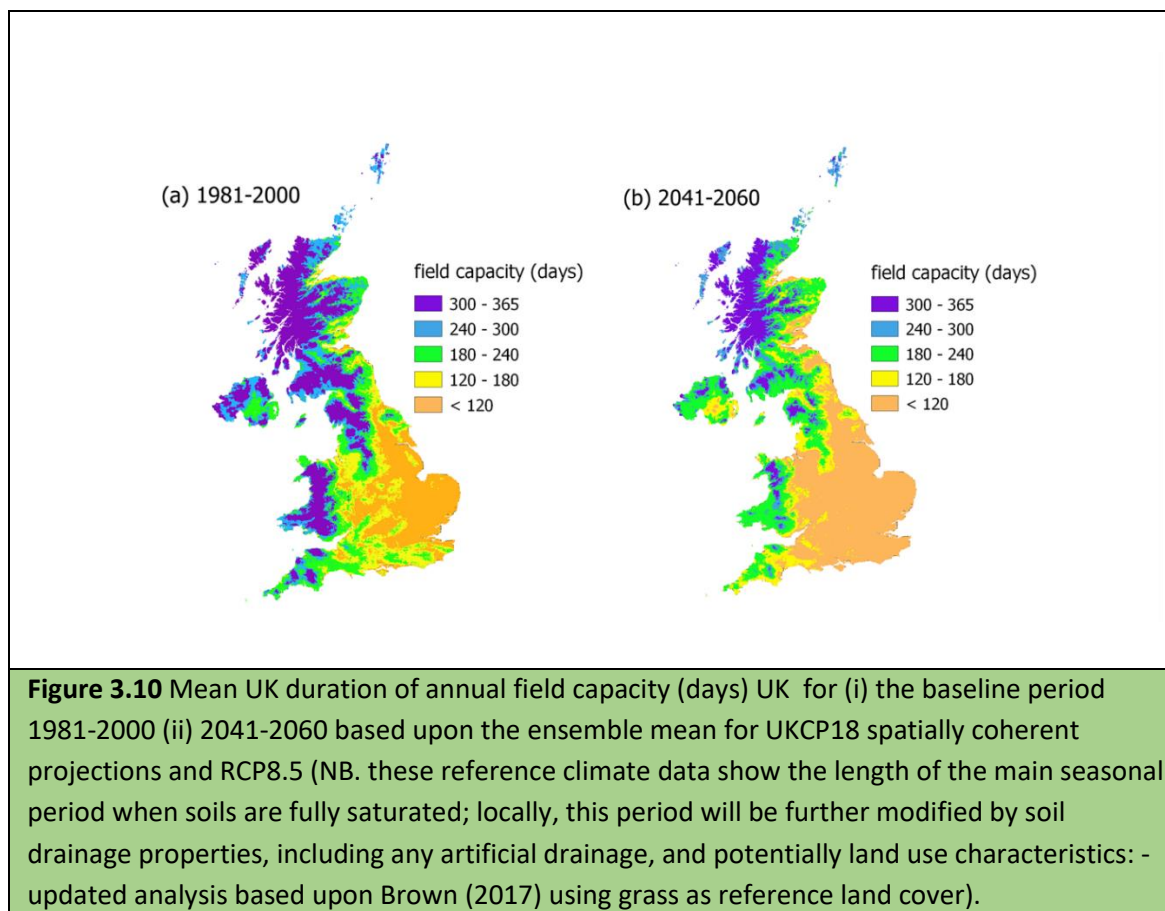
#### 3.7.1.2.1 Climate exposure and sensitivity

In terms of incremental change, general agroclimatic indicators clearly show a trend for warmer temperatures throughout the year (e.g., Arnell and Freeman, 2021), implying new opportunities will further develop, including the potential for increased crop growth and livestock to be outdoors more during winter months. However, higher temperatures will also have an important influence in advancing crop phenology, this being either a risk or opportunity depending on crop/cultivar. In practice, a longer growing season may also be interrupted or curtailed by increasing risks due to soil wetness from wetter winters, especially on more vulnerable soils (e.g., gleys) that are poorly drained (also depending on condition of field drains). The growing season is also increasingly likely to be disrupted by drought or heat stress from projected trends towards higher maximum temperatures and reduced summer precipitation (Chapter 1: Slingo, 2021; Arnell and Freeman, 2021). It is also possible that an earlier start to the growing season increases early-season frost exposure for some crops and locations, notably for fruits (Unterberger *et al.*, 2018) although this combined risk requires further analysis in the UK. Future climate projections also indicate a continued increase in solar radiation during the growing season, which may potentially benefit enhanced photosynthesis and plant growth, but also contribute to increase evapotranspiration and water demand.

Both risks and opportunities are related to the type of farming or forestry, notably choice of crop, livestock or tree species (and specialist cultivars), and the spatial and temporal dimensions of the climate effects that correspond with different magnitudes of climate change. The interaction of multiple climate parameters with other biophysical and socioeconomic factors, including the current plans for Net-Zero GHG emissions, means future assessment inevitably involves some uncertainty although more evidence is now available than with CCRA2. Combined analysis of climate and socioeconomic scenarios has shown how land use decisions, whether primarily determined by productivity (notably for food security) or in a multifunctional context, together with the influence of drivers such as technology, commodity markets, or consumer preferences (e.g., changing diets) can result in very different outcomes regarding land use change and risks/opportunity related to long-term sustainability (e.g., Harrison *et al.*, 2016).

Regarding interactive soil-climate constraints, changes in field capacity duration (Figure 3.10) imply a reduced period during which soil wetness constraints prevail for many eastern locations in England and Wales, although remaining a major factor for land use decisions in the west and north (Barrow *et al.*, 2020; Keay, 2020); similar findings using UKCP09 data have been reported from Scotland (Brown, 2017). By contrast, as highlighted in CCRA2, future climate changes imply that soil moisture deficits will increase and become an increasing constraint on land capability and hence land use options, especially for eastern locations and on drought-prone soils. Furthermore, the new data from UKCP18 suggests that the relationship between warmer drier summers and increased soil moisture deficits will be stronger, although detailed analysis of the changing seasonal pattern of soil moisture for agriculture and forestry is still ongoing. In Wales, analysis of soil-climate constraints using UKCP18 has shown that, although drought risk is rather limited at present, it becomes a much stronger risk factor for a significant proportion of the country (Welsh border, Pembrokeshire, Anglesey and north Wales) by the 2050s, and especially by the 2080s period (Keay and Hannam,

2020). Drought risk constraints can be alleviated by supplemental irrigation, but this will require additional investment (which may not be cost-effective for some land uses) and, as discussed below, in some locations water availability is very likely to become an increased concern for land managers.



Changing seasonal soil moisture patterns may have further implications for land management in autumn and spring too, with an extension of drier soils from the summer potentially benefiting autumn activities (e.g., harvesting, sowing), whilst wetter winters may constrain the drying of soils in spring. Present assessment of evidence, including recent evidence from Wales (Barrow *et al.*, 2020), supports this inference, but there are considerable uncertainties, notably because the changes will strongly depend on soil water drainage/retention properties (including ongoing performance of artificial field drains), but also because autumn/spring climate projections are more inherently uncertain than summer/winter and that these are projections of long-term averages hence masking considerable year-to-year variability which also constrains land management options (cf. Brown and Castellazzi, 2015). An important issue to recognise therefore is that we currently have rather limited evidence regarding how interannual variability in seasonal conditions will change into the future, and this variability also has a significant influence on land use decisions, especially for arable agriculture because optimisation of production is based upon tightly-managed schedules. This includes the effects of changing spell lengths (notably duration of dry/wet periods through the growing season and its critical phases). Full investigation of variability-related risks and opportunities as derived from analysis of UKCP18 data has yet to be published.

As discussed further for soils (Risk N4), in addition to findings from UKCP18 (Chapter 1: Slingo, 2021), new evidence from ensemble modelling (Spinoni *et al.*, 2018) suggests an increase in drought frequency, notably for southern and eastern UK, and moderate increase in drought severity, notably for southern UK, with these changes becoming more pronounced with time (comparing the 2071-2100 period with the 2041-2070 period). This increase in drought frequency and possibly also severity has major implications for water availability for agriculture and potentially some forestry enterprises: the increase in local soil moisture deficits may mean some crops and land uses become unviable based upon current use of water resources.

CCRA2 identified how future climate change will have major implications for land capability. More recent analysis using UKCP18 with the ALC for England and Wales (Keay and Hannam, 2020; Keay, 2020) has provided further information, suggesting a reduced area of grades 1 and 2 (excellent quality and very good quality), with this land being downgraded primarily to grade 3a/3b (good quality and moderate quality) by 2050 and in some areas downgraded further to grade 4 (poor quality) by 2080 (all emissions scenarios). Inferences using an assumed 'medium' and 'high' emissions scenario also suggest that some land that is currently ALC 3a/3b will be downgraded to ALC 4 by 2080, particularly in the 'high' emissions scenario. This indicates that a significant proportion of existing good quality land would become marginal for arable uses, primarily based upon drought risk criteria. Similar findings for Scotland, regarding increased drought risk and land capability, were reported in CCRA2 (based upon UKCP09), although the risk in Scotland is projected to be proportionately smaller. No equivalent analysis for Northern Ireland on future changes in ALC has been completed to-date.

CCRA2 highlighted that changing future climate conditions imply that the distribution of crop and livestock production would be required to shift in response to changing land capability as a form of large-scale adaptation required to maintain production. Further research provides more support for these inferences. Using higher resolution climate modelling (1.5km scale) with a high climate change scenario (RCP8.5), Ritchie *et al.* (2019) found that summer drying by the end of this century (compared to a 1998-2008 baseline) could contribute to loss of suitability for arable land in eastern UK and an increase in the west. Moisture deficits in the east could potentially be alleviated by increased irrigation but under this scenario the magnitude of increased crop water demand would be very likely to exceed local supply with water resource zones in the south and east shown to become increasingly water-stressed with a larger supply-demand deficit.

#### 3.7.1.2.2 Arable and Horticulture Crops

These large-scale changes also have major implications for the relative geographic suitability of different crops. Suitability modelling of a wide range of crop species has been developed for Wales (Bell *et al.*, 2019) based upon UKCP18 data and related ALC biophysical indicator criteria showing that general trends in suitability change over time following a similar pattern for most crops between present day and 2080. This general pattern is for a decrease in suitable area for most species due to increased drought risk constraints, although the results are based upon no further adaptation (e.g., through genetic improvement programmes), and for some crops currently considered as novel or niche there may be opportunities (see Risk N9).

The underlying challenge of providing adequate water supplies to deliver production goals has been further emphasised by new results from the CCC Water Availability study (HR Wallingford, 2020). Using UKCP18, this study found a similar increase in the supply-demand deficit for water-stressed areas (most notably south and east England but also very likely to extend to other areas) compared to similar work for CCRA2 and that agricultural water availability would be ultimately constrained by decisions on environmental flow requirements in the future climate, especially for a 4°C world compared to a 2°C world. These findings are consistent with other evidence for reduced water availability. The probability of annual abstraction being close to the maximum licence limit has been shown to increase significantly when comparing baseline (1961–1990) and future (2071–2098, based upon UKCP09 data) periods in selected catchments, based on observed relationships between annual weather and irrigation abstraction in three licence usage groups (Rio *et al.*, 2018). In addition, the same study used river discharge thresholds as defined for mandatory drought restrictions to assess the annual probability of surface water abstraction restrictions. The annual probability of having less than 20% licence headroom in the highest usage group is projected to exceed 0.7 in 45% of the management units, mostly in south and east England, whereas in central and western England an increased risk of drought restrictions occurring was detected due to the lower buffering capacity of groundwater on river flows, with the annual probability of mandatory drought restrictions reaching up to 0.3 there in the future (2071–2098) period.

To complement the more general information on changing capability and suitability, new evidence is available on risks and opportunities for specific crops, and for livestock, including analysis at larger scales such as European level. Analysis of a series of climate metrics indicating damaging thresholds for UK winter wheat projects conditions for wheat production to remain favourable with heat stress remaining relatively low until 2050<sup>13</sup> although winter/spring waterlogging may become an increasing factor (Harkness *et al.*, 2020).

Similarly, Trnka *et al.* 2015 analysed a range of adverse weather indices for European wheat production (2081–2100 compared to 1981–2010), for different climate change projections. The main finding for the UK was the dominant effect to be field inaccessibility due to wetness. Although this only has an infrequent influence at present (ca. 1–5% risk in each year) for the main production areas of southern and eastern England, in the 2081–2100 period this risk increased in frequency (mainly a 5–10% risk for a model simulating 4°C global warming at the end of the century<sup>14</sup> or 10–25% risk for a model simulating 5°C global warming at the end of the century<sup>15</sup>; but smaller increases at less than 4°C global warming). However, the rest of the UK continued to experience increased frequency of wetness-related inaccessibility constraints in future, meaning shifting wheat production to new areas as suggested above based on decreased summer water availability may be constrained by wetness factors from increased winter precipitation. Phenological and agroclimatic modelling applied to climate projections reaching 2°C, 3°C, 4°C and 5°C global warming at the end of the century<sup>16</sup> suggest conditions may remain generally favourable for oil seed rape (Pullens *et al.*, 2019). However, significant uncertainties and knowledge gaps remain, and climate change analysis

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<sup>13</sup> On pathways to between 1.7°C and 5.4°C global warming by 2100, projected by the CMIP5 ensemble driven with the RCP4.5 and RCP8.5 concentration pathways

<sup>14</sup> The GISS climate model driven with the RCP8.5 concentrations pathway

<sup>15</sup> The HadGEM2-ES climate model driven with the RCP8.5 concentrations pathway

<sup>16</sup> GISS and HadGEM2-ES driven with the RCP4.5 and RCP8.5 concentration pathways

has not yet considered the full interaction of different climate and non-climate parameters, despite advances in use of ensemble modelling (multiple climate and crop models) (Martre *et al.*, 2015; Rodríguez *et al.*, 2019).

Regarding drought risk, and specifically its influence on UK wheat yields, although the evidence indicates an increased risk, there remains significant uncertainty on the magnitude of this risk. Analysis by Clarke *et al.* (2021) has shown that modelling results based upon response functions derived using drought severity indicators are rather dependent on the indicators used, especially when the interacting effects of changing crop calendars and CO<sub>2</sub> fertilisation effects on yield are not incorporated, highlighting the need for a more integrated assessment including ecophysiological feedbacks with soil moisture deficits.

A key issue remains the interaction of changing CO<sub>2</sub> concentrations with other parameters. Recent, European-scale analysis for 1.5°C and 2°C global warming for a range of crops suggests that negative productivity effects from climate change may be partially offset by productivity gains from elevated CO<sub>2</sub> (Hristov *et al.*, 2020). However, the results are very sensitive to the assumptions used, including management factors, crop or cultivar, and spatial and temporal variations in the interacting variables (including soil properties and interannual seasonal variations) based upon the assumed crop growing area. This is especially applicable to assumptions regarding nitrogen timing and method of application in the context of prevailing weather conditions, and hence N accessibility to crops and implications for yield.

Regarding wheat yield quality, work from other countries continues to show that elevated CO<sub>2</sub> levels may have important implications, notably through reduced N and protein content but potentially also other nutritional values such as Zn content (e.g., Verillo *et al.*, 2017). However, these country analogues may not be directly applicable to UK. Furthermore, model analysis suggests that managed genotypic adaptation may maintain or even enhance wheat protein concentration (Asseng *et al.*, 2019).

#### 3.7.1.2.3 Grasslands and Livestock Production

For grasslands, recent analysis supports previous CCRA2 assertions of a longer growing season that may be constrained by soil wetness factors in west and north UK regions (Phelan *et al.*, 2016), although, as shown by analysis in England, Wales and Scotland, the period of maximum wetness (field capacity) may shorten depending on assumptions regarding field drainage system maintenance (Brown, 2017; Barrow *et al.*, 2020). Analysis using UKCP09 low and medium emission scenarios for 2050 (compared to 1961-90 baseline) using a metamodel approach indicates increased GB productivity for rotational and permanent improved grassland (ca. 25% and 10% respectively) but not for rough (unimproved) grassland (Qi *et al.*, 2018). Together with improved management (notably N use efficiency) these productivity gains may provide enhanced capacity for land sparing as assumed under the Net Zero GHG scenario. There is also some evidence, as noted above regarding the present climate, that elevated CO<sub>2</sub> may benefit grassland productivity. However, future climate changes towards higher temperatures and a general increase in summer soil moisture deficits, as noted above, may also affect species composition of the sward, quality of grass and other forages (Abdelgawad *et al.*, 2014; Lee *et al.*, 2017; Dellar *et al.*, 2018). This has implications for livestock

productivity and potentially for CH<sub>4</sub> emissions from livestock due to forages becoming more fibrous and of decreased nutritive quality with a lower nitrogen concentration.

Livestock are also likely to be directly affected by projected increases in temperature, especially when combined with humidity. The Thermal Humidity Index (THI) defines suboptimal and critical threshold levels of high temperature and humidity which cause stress in livestock, therefore affecting productivity (Dunn *et al.*, 2014). These limits are currently more of a productivity issue for other countries with a warmer climate than the UK but if projected future temperature increases are also accompanied by periods of higher humidity, this will increase the frequency of 'suboptimal' and possibly even 'critical' conditions. Analysis by the CCC Thresholds project (Jones *et al.*, 2020) of climate risk factors for milk production using the temperature component of the THI index and a very rapid global warming pathway to 4°C in the 2060s<sup>17</sup> projects that suboptimal conditions would become more frequent in southern and eastern England by 2050, assuming humidity levels remain similar to present. This is a low-likelihood, high-impact scenario, but the impacts may also represent those of an equivalent level of global warming reached at a later date (see Chapter 2: Watkiss and Betts, 2021). Analysis by Fodor *et al.* (2018) using the UKCP09 11-member PPE has generally indicated low average annual milk production losses from the THI relationship, but with considerable interannual variability, with the hotter locations projected to show an annual milk loss exceeding 1300 kg/cow by the 2090s (ca. 17% of today's productive capacity). In order to address some of the key uncertainties, this study also developed a more biologically-appropriate model and concluded that SW England is the region most vulnerable to climate change economically because of the combination of high heat stress with high dairy herd density, such that income loss for this region by the end of this century may reach £13.4m in average years and £33.8m in extreme years (regional farmgate milk production was £0.77bn in 2016, and when processed for dairy produce at £2.27bn). In the most affected regions, heat stress-related annual income losses for average size dairy farms were estimated at £2000-£6000 for average years and £6000-£14000 for extreme years. In addition, by the end of the century, it was also inferred that dairy cattle in large portions of Scotland and Northern Ireland will experience the same level of heat stress as cattle in southern England today. These general findings have also been confirmed using the more detailed 12km spatial ensemble data from UKCP18 which found that, based upon dairy farming remaining in its present locations, the area of greatest risk now and in the future would be south-west England (increases in heat stress of up to 60 days per year by 2070 compared to the baseline using RCP8.5 scenario), followed by Wales, the Midlands and northern England (Garry *et al.*, 2021). The same analysis found increases of less than 15 days across much of Northern Ireland and Scotland.

Climate change will also be likely to influence the productivity (and therefore supply) of bioenergy crops, with modelling capability for these species now also being improved (Littleton *et al.*, 2020). According to Defra census data around 129,000 hectares of agricultural land were used to grow crops for bioenergy in the UK in 2017, representing just over 2% of all arable land in the UK. Future warming-related increases in accumulated degree days are expected to increase growth rates and productivity of these crops, although in drier locations increases in soil moisture deficits are also very likely to affect growth potential, especially as these crops have high water demands. Warming will also mean that some crops such as poplar and miscanthus will also have a greater extent of land

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<sup>17</sup> UKCP18 regional projections driven by a global model with the RCP8.5 emissions scenario

with appropriate climatic suitability in the next few decades, providing opportunities for expansion including potentially into current marginal land.

#### 3.7.1.2.4 Forestry

In forestry, as discussed in detail in previous CCRA, projected increases in drought risk have important implications for some commercially important species, notably Sitka spruce. In Wales, tree suitability analysis has been conducted similar to the crop suitability analysis referred to above, focusing on Sitka spruce and sessile oak. This also shows a declining suitable area for commercial production due to increased drought risk, although this does not preclude trees being grown for non-production purposes, including for ecosystem services such as flood mitigation, carbon storage, and supporting biodiversity (Bell *et al.*, 2020). Alternatively, commercial production may adapt to increased drought risk by developing a long-term planting strategy that focuses on tree species that are more resilient than the 2 indicator species used for the analysis, although this has not occurred yet.

Recent analysis has also aimed to quantify risks to current timber production in Scotland using a scenario reaching approximately 5°C global warming at the end of the century<sup>18</sup>, as modelled over a 50-year rotation using the Ecological Site Classification (ESC) (Davies *et al.*, 2020). This projects Sitka spruce to continue to maintain an economically viable production level over most of Scotland but increased drought risk in some regions, notably central and eastern Scotland, implies that higher drought tolerance of alternative species will mean they have competitive advantages. This finding would support an increased emphasis on species diversification strategies that also have other co-benefits (e.g., for biodiversity and as resilience against pests/pathogens).

To a varying degree, trees have evolved with relatively high levels of phenotypic plasticity in order to tolerate environmental changes in situ over their long lifetimes, and this will confer some additional resilience whilst genetic adaptation through natural selection occurs over the longer time taken for generational turnover. However, new evidence also suggests that there may be limits to this acclimation when repeated extreme droughts occur, which would be consistent with increased future drought frequency in UKCP18 (see Chapter 1: Slingo, 2021). These repeated droughts may have a more pronounced effect on tree productivity and mortality because subsequent droughts apparently have a greater impact than the initial drought event, especially for conifers, and therefore that acclimation is limited (Anderegg *et al.*, 2020).

However, as highlighted throughout this evaluation, multiple factors act together to influence water-use efficiency (WUE) in plants and hence drought risk, including also changes in CO<sub>2</sub> and atmospheric deposition of N and S pollutants. Large-scale analysis of CO<sub>2</sub> fertilisation effects suggest annual biomass increments could increase by 15-25% by 2050 (e.g., Terrer *et al.*, 2019) but this will also be strongly dependent on local factors that influence nutrient availability, WUE, and drought sensitivity. Recent analysis has investigated changes in these factors for four tree species in twelve forests across climate and atmospheric deposition gradients in Britain (Guerrieri *et al.*, 2020)

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<sup>18</sup> SRES A1FI scenario



showing considerable variation in WUE due to interactions between climate and atmospheric drivers (for oak and Scots pine), but also variations due to an age effect (for Sitka spruce). Increase in WUE was mostly associated with increase in temperature and decrease in moisture conditions across the GB north-south gradient when interpreted over a 30-year period, and this appeared to dominate over the atmospheric deposition effect, although forest stand age was a confounding factor especially for Sitka spruce.

#### 3.7.1.2.5 Flooding, Erosion and Wildfire Risks

Regarding extreme events, future climate projections imply increased risks from both fluvial flooding and coastal flooding to agricultural land (Sayers *et al.*, 2020) when analysed over a period of years as represented by the extent of flood risk for land currently defined in planning systems as best quality (therefore not yet including future projections of changing land capability as described above). These findings imply increased risks for agricultural productivity during the individual years when flooding prevails, although changes in flood frequency will be the critical factor. These results also suggest that the projected magnitude of flood risk has increased since similar work for CCRA2 (although methodological variations should also be noted). For coastal flooding, the increased risks are more manifest for England (apparently very little change for Scotland and Northern Ireland), whereas for fluvial flooding significantly increased risks are highlighted for all countries but with the highest changes in risk for Wales. The increase in risk is more pronounced for a pathway to 4°C global warming in 2100 compared to 2°C.

These results are based upon land affected by a major flood event (1 in 75-year event) and further work to investigate changes in the frequency and extent of flooding together, including for smaller-scale localised events, will also be required because it is the frequency of flooding that influences land use decisions for a particular parcel of land. Also, the season when flooding occurs can be critical, with some land uses (e.g., grassland) often less sensitive to winter fluvial flooding. Coastal flooding usually has more severe ramifications as saline intrusion necessitates expensive land remediation activities to restore production. In addition, although Sayers *et al.* (2020) have investigated changes in surface water flooding risk, further analysis is required to ensure applicability to agricultural land because this needs to include the key role of agricultural drainage with regard to spatial and temporal changes in the water table.

A further issue is that as sea levels rise, some low-lying catchments that are currently drained by an effective elevational gradient to the sea (i.e., by gravity) will need to be pumped with increasing frequency. Similarly, those catchments that already require the assistance of pumped drainage will require additional pumping capacity. In some catchments, an increase in river flows in combination with sea-level rise will provide an additional compound risk for drainage infrastructure.

**Table 3.17** Increased area of current best quality agricultural land at risk of major flooding (1 in 75-year return period) assuming no further adaptation (i) coastal (ii) fluvial (Source: Sayers *et al.*, 2020)**i) Coastal**

Assets at significant risk	Baseline (Ha)	2050s on a pathway to +2°C in 2100	2080s on a pathway to +2°C in 2100	2050s on a pathway to +4°C in 2100	2080s on a pathway to +4°C in 2100
BMV land England	68,796	102%	128%	128%	154%
PAL Scotland	11,082	5%	8%	9%	14%
BMV land Wales	10,726	21%	44%	45%	74%
BMV land N. Ireland	65	0%	0%	0%	0%

**ii) Fluvial**

Assets at significant risk	Baseline (Ha)	2050s on a pathway to +2°C in 2100	2080s on a pathway to +2°C in 2100	2050s on a pathway to +4°C in 2100	2080s on a pathway to +4°C in 2100
BMV land England	259,248	21%	15%	22%	20%
PAL Scotland	90,727	26%	31%	38%	49%
BMV land Wales	52,413	47%	48%	57%	70%
BMV land N. Ireland	3,442	10%	18%	22%	37%

BMV land permanently lost to future coastal erosion has also been projected for England using extrapolation of NCERM data (Jacobs, 2018). For the 2050s, a central estimate (50% confidence level) of 240ha lost has been derived with an upper estimate (5% confidence level) of 320 ha. Equivalent estimates for 2100 are 545ha (central) and 754ha (upper), or if the erosion and movement of complex cliff landforms are included, year 2100 estimates would be 550ha (central) or 1450ha (upper) (Jacobs, 2018). Equivalent data for the rest of the UK have not been available but are provisionally assumed to be smaller due to the lesser quantity of equivalent higher quality agricultural land.

For wildfire risk, the current evidence suggests that risk magnitude increases broadly in line with increased temperature change over time and therefore is greater for higher climate change scenarios (i.e., greater for 4°C global warming compared to 2°C) (Belcher *et al.*, 2021). In terms of vulnerability, wildfire may be a more notable risk for forestry when compared to agriculture,

although the greatest increases in risk exposure are indicated for southern England where agricultural productivity is the dominant land use as compared to the northern UK where most of the land used for forest production services is situated.

#### 3.7.1.2.6 Knowledge Gaps

Collectively, assessment for this topic shows that the quality of evidence has improved since CCRA2. This includes new studies using high resolution climate models that better represent extremes (e.g., Ritchie *et al.*, 2019) although limitations remain in understanding how different types of adverse event affect crop yields, especially when using monthly data (see Falloon *et al.* 2014; Franke *et al.*, 2019, 2020). Inter-comparison programmes (e.g., Agricultural Models Intercomparison Project-AGMIP; Modelling Agriculture with Climate Change for Food Security — MACSUR) represent important advances in understanding capability of different models but are still constrained by differences in methods, assumptions and datasets etc. Much of the existing modelling work also does not fully include the interacting effects of increased CO<sub>2</sub> with climate change parameters or its interaction with water use efficiency and N uptake. Therefore, our assessment recognises that considerable uncertainty remains regarding how much potential yield gains from elevated CO<sub>2</sub> and enhanced photosynthesis productivity will be offset by climate-related deficiencies such as water stress and heat stress. We also have limited information on combined effects with other air quality parameters (e.g., changes in ozone (O<sub>3</sub>) concentrations). Regarding yield quality, there is some experimental evidence that elevated CO<sub>2</sub> will reduce grain protein concentration and gluten protein concentration, and therefore bread quality (Fernando *et al.*, 2015), but more evidence is needed on this topic (changes would be expected to also be strongly influenced by cultivar, and the timing and quantity of applied nitrogen in addition to CO<sub>2</sub> concentration). In addition, evidence suggests existing crop models are better at simulating water stress impacts than water surplus effects (nitrogen losses, diseases, anoxia, harvest conditions) (Lecerf *et al.*, 2019).

Finally, it should be noted that a production-related risk for which there is currently limited information is post-harvest storage of produce. Increased temperatures and related issues with moisture or humidity may have implications for the effective storage of different agricultural or forestry outputs, especially for the more sensitive crops (e.g., potatoes). This may be further exacerbated if the crop is already of reduced quality when harvested, and then storage may lead to further deterioration, thereby potentially reducing effective storage times for some produce unless additional investment in enhanced storage facilities occurs. Further investigation would therefore be beneficial on this topic, such as through methodologies that explore changes in storage degree days above defined thresholds for specific crops (both with and without further adaptation).

#### 3.7.1.3 Lock-in (N6)

Land allocation and management decisions often show considerable inertia and therefore can be slow to change in response to changing drivers. In addition, some socioeconomic drivers can encourage a continuation of existing practices in contradiction of requirements to adapt to a changing climate. This leads to a form of path dependency where present and future decisions can still be strongly influenced by the past, which can lead to a lock-in risk such that the pattern of land use remains a product of historic drivers rather than present conditions. For example, past trends

have seen a shift away from mixed agriculture and towards more specialisation and less diversification in both farming and forestry (Food, Farming & Countryside Commission, 2021). Also, plant breeding has produced greater yields but with a greater reliance on artificial fertilisers to supply nitrogen and other key minerals. These path dependencies may therefore act as a risk amplifier as climate change continues to diverge from the climates of the past. The risk is hence that productivity is additionally compromised by continuation of past land use decisions when a transition towards new and sustainable production systems should be occurring. Furthermore, these underlying socioeconomic factors that reinforce a continuation of past decisions may also be a contributory factor towards negative impacts for environmental quality.

The reasons for this inertia and lock-in require further analysis but are typically associated with access to machinery and equipment as well as knowledge and skills, together with the role of culture and traditional practices. To address these issues will require improved outreach and knowledge exchange in addition to funding support for capital assets, potentially also including new technology.

The longer lifetimes involved with forestry would imply a distinctively high potential for lock-in risks, hence the greater need, and often increasing awareness for anticipatory planning that includes a different future climate. The challenge for the forestry sector is then how and when to put this anticipatory approach into existing practices, as related to key decisions on stand management and rotation lengths before harvest. In reality, harvest cycles and production figures often differ from optimised projections as represented by planning through notional yield classes for tree species and location.

#### 3.7.1.4 Thresholds (N6)

Plant physiological and productivity thresholds related to bioclimate factors have been investigated for many years in agriculture and forestry as a key influence on species selection and therefore land allocation. For example, classic papers on crop physiology have shown the importance of the minimum water content required in the grain for wheat germination (35- 45%), which is related to the seasonal climate moisture balance, and exponential relationships between growth in cereals and absorbed solar radiation (Gallagher *et al.*, 1976; Gallagher and Biscoe, 1978). This has facilitated interpretation of yield to climate parameter relationships for different crops, including the familiar 5.5°C minimum threshold for grass growth used in standard growing season metrics. (e.g., as recommended by the UN FAO). Thresholds are therefore incorporated in planning tools such as for land capability classification and the ecological site classification for forestry decision-making based upon associations with physiology and plant performance (using metrics and thresholds for growing degree days, moisture balance, wind exposure, frost days etc.).

Regarding frequency of extreme conditions, the CCC Thresholds project (Jones *et al.*, 2020) investigated heat stress in winter wheat using projected changes in maximum temperature (3 consecutive days exceeding threshold 35°C during grain-filling, which presently occurs during July). Although this threshold is not exceeded at present or for a global +2°C change when following a RCP8.5 scenario, it is exceeded in a +4°C world where the threshold is exceeded for around 3-8 days/decade in the Midlands and SE England, which are both important wheat-growing areas. The same study also analysed the implications of heat stress in dairy cattle and the implications for milk

production using the temperature-based component of the established thermal humidity index, again finding a significantly increased risk of suboptimal conditions by 2050 with the RCP8.5 scenario. However, as highlighted above, temperature-based thresholds are often complex and will not occur in isolation and therefore effects are difficult to capture through simple indices (cf. Siebert *et al.*, 2017). For example, with winter wheat yield, moisture also typically becomes a critical risk factor at higher temperatures, or for dairy cattle and milk production, humidity interacts with temperature to determine stress levels. This interaction of multiple variables in a changing climate makes identifying discrete thresholds more difficult to identify with certainty for use in adaptation planning.

Further work is therefore required on heat stress, including the key role of humidity. Analysis by Kennedy-Asser *et al.* (2021) using both UKCP18 and CMIP5 climate models, has shown that model error in capturing characteristics of extreme heat generally reduces when using heat stress metrics with a larger vapour pressure component, such as simplified wet bulb global temperature (sWBGT). Similarly, other metrics, such as those based upon enthalpy, have been identified as more biophysically realistic in understanding heat stress for livestock, including in indoor settings (de Castro Júnior and da Silva, 2021).

A more multivariate approach to threshold analysis was used by Jones *et al.* (2020) to investigate implications for woodland productivity, in this case using a climatic moisture deficit (CMD) index to reflect the maximum accumulated monthly excess of evaporation over rainfall each year, and hence drought risk. This analysis used CMD thresholds of 200 mm for drought sensitive species (e.g., Sitka spruce, sycamore) and 300 mm for more drought tolerant species (e.g., Scots pine, Douglas-fir, oak, sycamore, hornbeam). Impacts on oak and beech were projected to be severe in a RCP8.5 high-end climate scenario (using a single model run), along with other deciduous woodland species. Impacts on conifers were mixed. All impacts vary geographically and were found greater in the south and east of the UK (including eastern and southern Scotland), affecting growth and timber quality, and are consistent with other analyses reported in this assessment on the effects of increased drought risk.

#### 3.7.1.5 Cross-cutting risks and inter-dependencies (N6)

Production is very dependent on water availability and soil fertility, both of which are declining resources in many areas of the UK and further influenced by climate change (for soils, see also Risk N4). Reduced water availability may mean irrigation for intensive agricultural and horticultural production will be in conflict with other water uses (including the needs of wetlands and freshwater biodiversity). Averting these water-related conflicts will require further development of improved abstraction and irrigation techniques, together with facilities for water storage to make more use of excess winter rainfall (including design features to avoid risks to water quality from overflow or other runoff). Especially in specialised horticulture, water efficiency gains may be also achieved by recycling of water and improved design of glasshouses or other types of cover (polytunnels etc.), but some designs may be detrimental to soil quality, and each will require further investment. In addition, maximising sustainable use of water resources in water-stressed areas will require enhanced collaboration, not just in the agricultural sector but with the wider range of users, in order to ensure resources are available at the most crucial times (Knox *et al.*, 2018).

Evidence also suggests that in a business-as-usual scenario, climate change will have further negative effects on the externalities associated with intensive agricultural production (e.g., Royal Society, 2020; Food, Farming & Countryside Commission, 2021). In addition to pressures for agricultural intensification, including 'land sparing' objectives associated with the Net Zero agenda (see below), similar indirect pressure to optimise production in specific locations may occur due to biodiversity objectives and allocation of a greater land proportion for protected conservation areas (e.g., nature recovery areas).

In the absence of improved practices, increased rainfall intensity and storm runoff will interact to increase the risk from excess nitrogen (N), phosphorus (P) and pesticide losses that are not taken up by plants, impacting on soil quality, water quality and climate change mitigation efforts (CO<sub>2</sub> and N<sub>2</sub>O emissions) (Arnell *et al.*, 2015; Lu *et al.*, 2017). Risk is greatest when application is associated with saturated soils or periods of high rainfall or when a large proportion of bare ground is exposed to surface runoff. Sediment loads from episodes of severe soil erosion during extreme rainfall events can also be a problem for water quality. Increased volatilization of ammonia fertiliser from higher evapotranspiration rates may also affect air quality and atmospheric emissions targets, although evidence is limited here.

Analysis of water quality interactions shows results are strongly influenced by assumed interactions between climate and land use change. Based upon an assumption of optimised land use that in a warmer drier climate would lead to a shift from arable to grassland in the Thames basin, analysis at 2 locations has suggested reductions in N concentrations but increase in P concentrations (Bussi *et al.*, 2017). Similarly, analysis in the Wensum, Avon and Eden catchments using high-resolution climate modelling and the UKCP09 weather generator has shown average winter P loads could increase up to 30% by 2050s, as exacerbated by agricultural intensification and will be limited only by large-scale agricultural changes (e.g., 20–80% reduction in P inputs) (Ockenden *et al.*, 2017).

Negative impacts on water quality may also become an increasing concern for irrigation supplies. As future summer river flows are projected to decline, reducing the dilution of pollutants and impacting on water quality (see Risk N11), then pathogen or other contamination of irrigation water may become a greater problem than present. Increased pollution of groundwater sources may also occur (e.g., from pesticides or nitrates), although evidence here is limited. Public health implications may become especially severe in some locations where high-value crops are grown, notably where land use is currently optimised for unprocessed 'ready to eat' produce including salads.

The projected trend towards increasing frequency of wetter winters combined with further agricultural intensification, including use of heavy machinery, indicates further risks from soil compaction unless precautionary measures are taken. Recent trends towards heavier agricultural machinery can cause increased pressures on soil resources, unless used only at appropriate times (Keller *et al.*, 2019). Compaction can affect yield and damage soil structure (e.g., reduced grass yields: Hargreaves *et al.*, 2019) whilst also causing increased flood risk (Alaoui *et al.*, 2019), nutrient runoff and water quality and N<sub>2</sub>O emissions through denitrification. As optimised agricultural production following current practices usually requires land has good drainage (both for access and for crop growth), field drainage systems are used to remove excess water but, in addition to causing

water quality problems, this can also contribute to increased flood risk downstream in some catchments (depending on drainage system and soil properties).

Pests, pathogens, and INNS (Risks N7 and N8) have important interactions with productivity in agriculture and forestry, both directly and indirectly. In some instances, these may have detrimental impacts on pollinators which are an essential requirement in the production of some crops (Vanbergen *et al.*, 2014, 2018). Both agricultural and forestry production systems can also have a large influence on landscape character (Risk N18), either positively or negatively. These wider implications will depend on whether changes in production systems (both for climate change adaptation and mitigation) are also developed in sympathetic accord with their wider landscape context.

There are also important interactions with other CCRA chapters. Farming and forestry are integral to a wide diversity of rural communities across the UK and those working on the land may have increased exposure to some climate-related health risks (Chapter 5: Kovats and Brisley, 2021). Cultural heritage associated with traditional agricultural/forestry practices are important to recognise in developing responses that protect both the natural environment and cultural heritage. In addition, negative impacts on productivity can have severe consequences for agriculture and forestry businesses, and associated sectors, notably in food and drink processing (Chapter 6: Surminski, 2021). Perception of these risks, notably relating to the impacts of changes in water availability, are variable across supply chain despite affecting not only growers (who are more directly exposed) but also others including packers, manufacturers, and wholesalers, which may further compromise the resilience of the whole chain (Zurek *et al.*, 2020).

Extreme weather can have further severe impacts on the full agricultural and food/drink supply chain to then affect the consumer. Following on from the negative effects of cold spring weather, then summer drought and heatwave in 2018, it was reported that between March and July, the UK wholesale farm-gate prices of the following commodities increased significantly: onions (+41%); carrots (+80%); lettuce (+61%); wheat for bread (+20%); strawberries (+28%); the average increased cost to the consumer was estimated at £7.15/month/household (Centre for Economics and Business Research, 2018).

Furthermore, implications of reduced productivity for domestic food supply can have consequences in terms of food security issues, especially in vulnerable communities, and therefore disruptions to food supply can have important implications for human health and policies to address societal inequalities (Chapter 5, Risk H9: Kovats and Brisley, 2021). Here there is also an important interaction between the domestic food supply and the changing pattern of international food supply (Chapter 7, Risks ID1, ID2: Challinor and Benton, 2021), with reduced supply of key food commodities associated with price rises and a further exacerbation of food poverty issues for vulnerable people and communities. Finally, agricultural production at present usually relies on local water supplies but a future shift towards increased agri-tech and large-scale intensified production systems will very likely mean it is increasingly reliant on utility networks and associated infrastructure which can be at risk of severe disruption, especially following extreme events (Chapter 4: Jaroszewski, Wood and Chapman, 2021)). These challenges for agriculture are further exacerbated because the UK

population is increasing (an additional 10 million people by 2050 following a central projection) and therefore more food will be required either from domestic or overseas sources

Regarding incomes in farming or forestry, reduced crop yields or impacts on the quality of livestock or timber produce can obviously be severely detrimental. However, the linkages are complex due to the influence of other factors, including markets and policy. For example, if crop yields are reduced on a large scale at international level, then global prices increase and an arable farmer may obtain a good economic return even with a limited farm output for that year, although a livestock farmer may face increased input feed costs. For example, the Russian grain export ban of 2010, which was a consequence of the effects of the extreme heatwave of that year on the grain harvest in that region, acted to increase global grain prices and make them rather more volatile.

### 3.7.1.6 Implications of Net Zero (N6)

The CCC (2020) Net Zero 2050 scenario pathways are predicated on crop yield improvement (through improved agronomy and crop breeding) and land sparing to enable additional C sequestration through afforestation and bioenergy crops. Assumptions on future crop yield improvement may be challenged by the climate-related risks to present and future production that have been described above. Hence, although the Net Zero scenario assumes climate-resilient crops are developed such that average UK yield gains increase by ca. 30% by 2050 compared to present (based upon an increase of wheat yields to 11t/ha compared to present 5-year average of 8.4t/ha), this does not fully recognise yet the considerable inter-annual variability in yield that presently occurs due to climate factors, including years such as 2018 and 2020 when yields were considerably reduced (each for different reasons). In addition, crop production areas show considerable variability from year to year as farmers adjust to the past year and prevailing conditions; this adjustment would be rather more constrained if overall production areas were reduced.

Furthermore, Net Zero assumptions based upon following an optimised land sparing pathway, in terms of land allocation objectives, are very likely to be affected by changing land capability throughout the UK, especially from eastern regions becoming drier (consistent with findings from UKCP18), and difficulties with yield stability due to both changes in the long-term climate and its interannual variability. These ongoing effects of climate change will therefore present a considerable challenge for delivery of the Net Zero goal. The default assumption in development of the CCC (2020) Net Zero scenarios to-date has been optimal adaptation to enhance production outputs; further work is now in progress to re-evaluate these assumptions as would be consistent with the assessment presented here. The challenge for crop breeding is to develop cultivars that can increase yields whilst also being resilient to the wide range of climate-related effects that can occur in the UK, including heat stress, drought risk, wetness factors (e.g., lodging), and pests and pathogens (see Risk N7), rather than just one of these factors in isolation.

In addition, most of the land use or land management options identified as likely to be beneficial for contributing to Net Zero, such as a shift towards higher stocking densities on permanent grassland or high sugar grasses for livestock forage, have yet to be fully investigated in terms of whether they will be also a robust option based upon future climate projections. Higher livestock densities on



grassland may have negative outcomes for soil degradation and water quality, especially in the context of more intense rainfall events and soil saturation or infiltration constraints (as associated with soil compaction), unless carefully managed. For forestry production (and associated carbon storage), if new woodland is targeted to be planted on land with high suitability, rather than land that is less suited for agriculture as occurs primarily at present, then there could be important benefits for achieving the Net Zero goal as this is likely to enhance production and carbon storage (unless occurring in locations susceptible to drought risk).

These interactions between a changing climate and agricultural or forest productivity have implications for previous studies that have attempted to 'optimise' production in specific locations. For example, optimisation studies for bioenergy crops in the context of Bioenergy with Carbon Capture and Storage (BECCS) schemes (e.g., Donnison *et al.*, 2020) require further investigation because they have not considered the additional adaptation requirements that may be required in the future, notably due to water availability.

Research is now further exploring synergies and conflicts between production goals and Net Zero. For example, yield and production changes for UK spring barley and hence supplies of malting barley have been investigated using UKCP09 weather generator data for the 2030s-2050s (Yawson *et al.*, 2018, 2020). Future land area available for barley production was defined pro rata from projected changes in agricultural areas assumed by the CCC central Net Zero GHG scenario. Although yields showed potential future increases due to climate warming and increased CO<sub>2</sub> concentrations, reduced available land area following Net Zero pathways meant that a production supply deficit for malting barley was estimated based upon continuation of current demand (especially from the drinks industry). Similarly, the CCC Balanced Scenario for Net Zero assumes average wheat yields increase ca. 30% to reach 11t/ha by 2050 (with other crops also showing similar gains) in order that the production area can be decreased, but as noted above crop yields have been rather variable in recent years with wheat yields in 2020 reduced by 17% at 7t/ha due primarily to climate factors. The CCC (2020) Net Zero report recognises that average yields have also tended to reach a plateau level after major gains towards the end of the 20<sup>th</sup> century. Therefore, if the cereal cropping area was reduced consistent with the same CCC Net Zero scenario, as required to spare land for bioenergy crops and new woodlands, then following current yield trends this would imply a significant production shortfall with potential further implications for domestic food supply. By contrast, allowing an increased cropping area to allow domestic food supply to have headroom to adjust to current patterns of yield volatility would require a greater emphasis and reliance on other innovations to meet the Net Zero goal such as Carbon Capture and Storage. The current focus on average yields in Net Zero scenarios is therefore yet to recognise that the average disguises considerable underlying interannual volatility which agricultural systems adjust for by varying crop production areas as a risk compensation measure.

The CCC (2020) Net Zero scenarios additionally assume improved productivity of conifer plantations (in terms of yield classes and carbon storage) which in our view seems realistic, at least in the medium-term. However, identifying suitable land for large-scale woodland expansion to deliver additional carbon sequestration as a key component of the Net Zero scenario will also require an adaptive approach (as currently under investigation by the CCC). For example, tree suitability modelling of new planting opportunities for sessile oak and Sitka spruce in Wales has found that

meeting the 152,000 ha target of additional woodland by 2050 in the context of protecting best quality agricultural land is only achievable through using land that is less biophysically suited, especially considering future climate change, or that different species may be required (Bell et al., 2020).

Finally, changes in demand driven by the Net Zero agenda could also have major implications for domestic production and the capacity to meet that demand. For example, a shift from a meat-dominated diet to a more vegetable-based diet may lead to requirements for increased cropping and in turn, irrigation demand. However, as a significant proportion of existing crops are used for animal feed, then more direct use of crops to supply human nutritional needs can potentially provide increased efficiency in land use compared to existing patterns. This would still require that the land used for cropping could consistently provide high-quality nutritious produce; as noted above, at present there are often considerable interannual variations in the quality of produce as well as quantity (with lesser quality produce often used as animal feed).

#### 3.7.1.7 Inequalities (N6)

As described above, the impact of adverse weather on reduced production can have serious consequences for livelihoods, especially in rural areas. This can act to exacerbate societal inequalities, including for occupational categories such as tenant farmers or seasonal workers (farming, horticulture, or forestry) that often have limited security or capital reserves. As also noted, the impacts of reduced agricultural production on domestic food supply can have important implications in terms of food availability and price, which can be especially severe for people on limited incomes.

Beyond these general inferences for those directly involved with the sector, there is currently no specific evidence for how societal inequalities may be affected by climate change risks and opportunities for agricultural and forestry productivity, although any resultant impacts on food availability and food price will obviously be a key concern.

#### 3.7.1.8 Magnitude scores (N6)

Magnitude categories (Table 3.18) are based on expert judgement of expected climate change impacts (risk and opportunity) across the full range of production outputs, as supported with quantitative evidence for some of these outputs (yields and national productivity etc.), but excluding impacts of pests, pathogens and INNS. The present magnitude score should be interpreted as at least Medium with high confidence (it is possible it may be higher but there is considerable interannual variability and this rating is taken to be for a multi-year average). For future periods, risk magnitude is assessed as High with medium confidence regarding average multi-year yields but the role of extreme events for individual years remains more uncertain.

**Table 3.18** Magnitude score for risks to and opportunities for agricultural and forestry productivity from extreme events and changing climatic conditions (including temperature change, water scarcity, wildfire, flooding, coastal erosion, wind)

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
<b>Northern Ireland</b>	Medium (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
<b>Scotland</b>	Medium (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
<b>Wales</b>	Medium (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)

### 3.7.2 Extent to which current adaptation will manage the risk and opportunity (N6)

When compared to agriculture, which shows generally low levels of proactive planned adaptation, forestry has more evidence of co-ordinated adaptation planning, mainly through public sector forestry and the activities of national forestry agencies. Confidence in this part of the assessment is limited because few studies have investigated adaptation issues at management level although there is a wider body of research for the land sector, extending beyond climate change responses (e.g., uptake of soil conservation measures – see Risk N4), that generally shows a disjunct between policy aspirations and actual actions as implemented on the ground by land managers.

### 3.7.2.1 Effects of current adaptation policy and commitments on current and future risks and opportunities (N6)

#### 3.7.2.1.1 UK-wide

This topic is situated within the policy domains of Defra (England), Scottish Government Agriculture and Rural Delivery Directorate (Scotland), Welsh Government (Wales) and DAERA (Northern Ireland).

Adaptation policy remains rather general in terms of objectives and mechanisms to maintain or enhance domestic agricultural or forest production, rather than to develop and implement specific actions. However, the position is further complicated by EU-exit regarding how new international agreements will modify the current policy landscape including how production objectives will interact with regulatory requirements, support payments, and associated cross-compliance obligations that will replace EU Common Agricultural Policy (CAP) obligations. In addition to the new UK Agriculture Act 2020 which will primarily cover England, policy implementation for the other nations is also similarly in transition and will have additional interactions depending on their level of alignment with other parts of the UK in addition to divergence from the EU CAP.

As many farms are reliant on subsidy support to augment income from production, the specific details of these policy developments will be crucial for determining both the productive capacity of farmers and also the interactions with the wider environment, into which adaptation responses will also develop and evolve.

This transitional phase means that, at present, only indicative rather than detailed information on the new policy landscape, including for both incentives and regulation, is available. Therefore, it is not clear at the time of this assessment how the role of markets and policy will act to shape decisions across different types of land use and land quality. For example, a rather different outcome might be expected on lesser quality or marginal land which is generally more dependent on subsidy support (notably agri-environment schemes) compared to more market-orientated decisions on higher agricultural quality where the current focus on production may be expected to continue. In addition, there are likely to be notable differences across countries and regions of the UK in terms of both policy support and favoured land uses. This uncertainty therefore constrains assessment of climate-related risks and opportunities and adds to the future uncertainty.

However, based upon current actions, and discussions with stakeholders, it is probably fair to highlight that the current policy emphasis in our view remains focussed on enhancing 'climate resilience' in agriculture (with resilience here interpreted as improved protection for current production systems), especially via genetics and crop breeding. Genetic improvement networks have been developed to help reduce the long lead times between development and implementation, which can extend to 15-20 years. Rather less emphasis is currently placed on developing good practice for anticipatory adaptation at farm level which may require a shift to new modes of production or alternative land uses. In consequence, the National Audit Office has previously found that Defra "has not provided the necessary guidance to enable farmers to plan how to adapt their businesses or how to work collaboratively with other farmers".

More generally, across the UK, advice to land managers is provided through updates that focus on the known linkages between seasonal/annual conditions and management requirements to achieve production objectives, as exemplified by the 'Forage for Knowledge' initiative, AHDB crop development reports, and guidance from forestry advisors. At the level of government agencies, guidance and advice is also provided to land managers in terms of nature conservation, soil protection, and water resources, including compliance with policy requirements. In some cases, this has been further extended to include climate change adaptation guidance (e.g., Natural England adaptation manual). However, it is also often recognised that there is a gap between aspirations and delivery in practice, often because guidance needs further refinement to meet specific local contexts (and this aspect is usually covered through payments to specialist consultants).

As reported in previous CCRA, and for which we interpret a similar comparison pertains for CCRA3, a clearer strategy and evidence of long-term adaptation planning is evident in the forestry sector as influenced by the longer time frame for trees to reach maturity and long-term plans for woodland expansion, especially to help achieve Net Zero objectives. In addition, there has been more emphasis, as shown in national forestry strategies, of the need for forestry production to be integrated within a multifunctional landscape and to provide multiple ecosystem services (including the role of woodlands in carbon storage, flood alleviation etc.). Some forestry grants also require that future climate projections are considered when selecting species for planting, in order to comply with the UK Forestry Standard (UKFS). A UKFS Practice Guide on adaptation is expected to be published during 2021 to help forest managers/owners meet the adaptation requirements of the UKFS. However, there is still limited information on how much of this adaptation guidance is actually being implemented, especially in the private forestry sector where evidence suggests adaptation actions have been more limited (e.g., Lawrence and Marzano, 2014). Climate change mitigation (often linked with carbon offsetting) often appears a stronger driver in land management objectives, although surveys do identify that adaptation is a priority issue for land managers (e.g., British Woodland Survey 2015 and 2020 – see Hemery *et al.*, 2020). However, surveys also identify that a significant proportion of woodlands remain 'unmanaged' and are not considered to be fulfilling their full potential (e.g., Royal Forestry Society, 2019).

Increasing awareness of wildfire risk is also reflected in policy developments, although this is currently more evident in the forestry sector than for agriculture. These developments include increased use of knowledge exchange to develop shared awareness of changes in risk and through ongoing developments for best practice in fire risk reduction, as represented by regional wildfire networks and national wildfire fora for England, Scotland and Wales. Nevertheless, there is also a concern that the level of awareness and engagement is variable (Gazzard *et al.*, 2016), possibly related to the level of recent experience with the hazard; this is reflected in the extent to which climate change adaptation is included in strategic plans, which for some locations is extremely limited (see also Box 3.1: Introduction).

Planning policy for land use is based upon protection of best quality land (BMV or PAL), although implementation of this varies across the UK with a higher sequential test to justify the use of this land for other purposes in Scotland and Wales compared to England. As identified in CCRA2, future projections of changes in land capability to 2050 and beyond are now available for most of the UK (excepting Northern Ireland) to provide a basis for forward planning, including recent developments in Wales through the Climate Suitability and Capability Programme (CSCP) initiative to provide

predictive agricultural land classification maps based upon UKCP18 for planning authorities. However, challenges remain in communicating this information to planners, including how to represent the reality that climate change can have multiple future pathways rather than to over-rely on one 'predictive' map in strategic planning. Use of forward projections in land use planning documents therefore remains very limited.

Regarding implications of risks to agricultural production affecting domestic food supply, Clause 17 of the new UK Agriculture Act 2020 sets out a duty for the UK government to report on food security to Parliament at least once every 5 years. In addition to domestic supply, reporting will cover a range of current issues relevant to food security including global food availability; supply sources for food, the resilience of the supply chain for food; household expenditure on food; food safety and consumer confidence in food (see Chapter 5: Kovats and Brisley, 2021; and Chapter 7: Challinor and Benton, 2021 for further details of these issues).

Another notable issue regarding negative 'externalities' arising from agriculture is that multiple schemes are available to the land manager, with some obligatory regulatory requirements and others as voluntary opt-ins. However, our assessment of the current position is that they are not often joined up to maximise their co-benefits, including for climate change adaptation. For example, the Catchment Sensitive Farming (CSF) initiative is an important development for addressing diffuse water pollution from agriculture in priority catchments (as required by Water Framework Directive targets and drinking water quality standards) but a catchment-sensitive approach is also required to better manage flood risk and low water flows, often in the same priority catchments. Without further policy development, this could lead to inadvertent adaptation trade-offs rather than synergies. However, it should also be noted that multi-stakeholder partnerships have become established in some catchments and are providing a more integrated approach to land/water interactions based upon local or regional contexts throughout the UK (e.g. 'Upstream Thinking' project in SW England; Tweed Forum in the Scottish Borders/Northumberland etc.).

#### 3.7.2.1.1.1 Flood risk management

The CCRA3 Floods Study (Sayers *et al.*, 2020) provided some indicative evidence on the level of additional protection that a continuation of current adaptation will provide for reduced flood risk on land that is currently identified as being of higher quality (BMV or PAL)(Table3.19). By comparison with the no adaptation results it can be seen that coastal flood risk would be significantly reduced for England and to a lesser extent for Wales (little change for Scotland and Northern Ireland), whereas for fluvial flooding it was found that there would not be much change in the area of land at risk.

The increased risk to agricultural land from flooding also is intended to be included in post-CAP plans for each administration, including a greater role for NFM in addition to protection for better quality farmland, although implementation details are still in development. It is therefore not yet clear whether current cost-benefit formulas used in options appraisal for flood and coastal erosion protection will be further refined to include the strategic value of the best quality farmland.

**Table 3.19.** Changes in land at significant risk of flooding (frequency of 1 in 75 year or greater) with continuation of current adaptation policies (i) coastal (ii) fluvial. Source: Sayers et al. (2020)

i) Coastal					
Assets at significant risk	Baseline (Ha)	2050s on a pathway to +2°C in 2100	2080s on a pathway to +2°C in 2100	2050s on a pathway to +4°C in 2100	2080s on a pathway to +4°C in 2100
BMV land England	68,796	68%	89%	89%	115%
PAL Scotland	11,082	5%	8%	9%	14%
BMV land Wales	10,726	21%	37%	37%	65%
BMV land N. Ireland	65	0%	0%	0%	0%
ii) Fluvial					
Assets at significant risk	Baseline (Ha)	2050s on a pathway to +2°C in 2100	2080s on a pathway to +2°C in 2100	2050s on a pathway to +4°C in 2100	2080s on a pathway to +4°C in 2100
BMV land England	259,248	18%	13%	19%	18%
PAL Scotland	90,727	26%	32%	38%	49%
BMV land Wales	52,413	46%	46%	57%	69%
BMV land N. Ireland	3,442	10%	18%	22%	37%

### 3.7.2.1.2 England

The UK Agricultural Act 2020 represents one of the most significant pieces of legislation for farmers in England for several decades. The Act sets out provisions for transition between 2021-2028 away from the former CAP subsidy scheme, replacing direct payments based on land area in agricultural production with a scheme providing payments for 'public goods'.

Agri-environment and single farm payments (and any other related grants) are, therefore, in transition to a new Environmental Land Management scheme (ELM - see Risk N1 for further details) from 2024, also including productivity grants (e.g., for new technology). As components of ELM, the Sustainable Farming Incentive will be aimed at facilitating land management in an environmentally sustainable way, Local Nature Recovery will aim to deliver local environmental priorities and Landscape Recovery will aim to deliver landscape and ecosystem recovery through long-term land use change projects.

This new approach will also remove an obligation to farm the land that existed under the EU CAP, potentially therefore facilitating greater integration with forestry and agro-forestry uses. Current cross-compliance arrangements are, therefore, being phased out and will be replaced by new requirements, including plans for an improved inspection and enforcement process, and common regulations for animal welfare. Current plans also indicate that support packages may also aim to add additional incentives that support important local or landscape-scale benefits, which could help address the wide diversity of different contexts for land management. However, specific consideration of how ELM payments and the other schemes will support adaptation to climate change is missing at the time of this assessment.

The Forestry Commission (2020) has produced adaptation guidance for woodland management ('Managing England's woodlands in a Climate Emergency') that includes diversification of species, genetics, and stand structure. This guidance suggests that where timber production is a high priority in the woodland management objectives, or the planting is not adjacent to a site recognised for its local genetic integrity, that an assisted migration approach is considered, also contingent on an owner's attitudes to risk. Assisted migration strategies are suggested based upon provenances from 2 degrees latitude south of the planting site, as these generally outperform the local provenance and this is considered a safe distance over which to transfer material, or from a more forward-looking (but potentially riskier) perspective upon provenances from up to 5 degrees latitude south that match climate change projections out to 2050.

A new FCERM government statement and strategy includes farmland within its generic framework of 'resilient people and places' and aims to go further than most existing policies by considering resilience in the context of different future climate change scenarios through adaptive pathways.

#### 3.7.2.1.3 Northern Ireland

In Northern Ireland, the 2014 'Going for Growth' strategy, which aims to enhance production capacity, has recently been complemented by a Sustainable Agricultural Land Management Strategy developed by an Expert Working Group (2020). Although the latter only contains rather limited reference to the need for adaptation in the context of improved 'resilience against extreme events', it is notable for proposing a progressive roadmap that recognises the synergies between production gains and improved environmental outcomes. In particular, it highlights current issues with poor soil quality and sub-optimal grass utilisation, together with a significant proportion of land with insecure tenure, and proposes making soil health a central focus of the strategy complemented by considerable improvements in soil/water monitoring (including use of GPS and LiDAR technology) and land manager engagement in policy development. Based upon these developments, it is proposed that production capacity could be enhanced so that in terms of grass utilisation this would achieve at least one extra tonne of dry matter per hectare and with improvements in grass and silage quality of 5 to 8%.

#### 3.7.2.1.4 Scotland

In Scotland, the SCCAP2 highlights knowledge exchange schemes, such as Farming for a Better Climate and Monitor Farm Scotland, which aim to take a whole farm approach to improve both productivity and sustainability, although much of the emphasis to-date has been on reduction of farmland GHG emissions. Scotland's Forestry Strategy presents a 50-year vision based upon



principles of sustainable forest management and a 10-year framework for action, including commitments to increase woodland cover to 21% of total land area by 2032, with the 2020-21 12,000ha/yr woodland expansion target being incrementally increased each year to deliver 18,000ha/yr for 2024-25. SCCAP2 also reaffirms the importance of further development of the national Land Use Strategy for adaptation planning, especially for the uplands, although many of the future challenges also require equal attention for the lowlands and upland-lowland interactions (and rural-urban interactions). This latter issue is especially notable because SCCAP2 and the Land Use Strategy both advocate an ecosystem services framework and recognise challenges in correcting imbalances between agricultural productivity and other ecosystem services, together with the need for integrated planning across multiple land uses to ensure a sustainable flow of services. The Land Use Strategy for 2021-2026 has recently been launched and a development plan is expected to follow later in 2021. Work is also in progress to update the Land Capability for Agriculture classification system based upon climate change data from UKCP18 to provide a basis for forward-based land use planning.

#### 3.7.2.1.5 Wales

The Welsh Government has published 'Sustainable Farming and our Land' with initial plans for post-EU-exit arrangements. This includes proposed objectives to ensure ecosystem resilience consistent with the duty set out in the Environment (Wales) Act 2016, although explicit details for climate change adaptation actions remain to be developed. A national forest strategy 'Woodland for Wales' was released in 2018 recognising the importance of woodlands and including a new short-term target to increase woodland cover by at least 2000ha/yr from 2020 to 2030 and beyond, although in previous years very little new woodland has been created. In 2019, the second Welsh National Adaptation Programme 'Prosperity for All: Climate Conscious Wales' identified plans to integrate adaptation into the Sustainable Farming Scheme for Wales via evidence reviews, research, working group proposals and a Sustainable Brand Values Scheme, together with ongoing work to implement new land capability maps and other information from the Capability, Suitability and Climate Programme (as referred to above) as a basis for strategic land use planning. In addition, Farming Connect provides knowledge exchange, innovation and advisory services for farming and forestry businesses in Wales and evidence gathering to implement climate-smart actions in the red meat and dairy sector are being supported through Aberystwyth University. Guidance has been produced by Natural Resources Wales (Natural Resources Wales, 2017) looking at forest diversification of species, genetics, and stand structure.

Welsh Government published its new FCERM national strategy in October 2020. In the strategy, the Welsh Government commits to working with partners to encourage appropriate land management practices and NFM schemes to reduce run-off and soil erosion.

#### 3.7.2.2 Effects of non-Government adaptation (N6)

As referred to above, short-term reactive responses at farm level still tend to dominate in agriculture, whereas the longer planning horizons in forestry appear to have encouraged more longer-term planning, at least in the public sector. Some adaptation measures have long lead times, including development of climate-resilient cultivars or livestock genetic programmes, and measures to adapt to water availability constraints in drier areas. For agriculture, an important yield gap (and hence production gap) remains between what is technically feasible and the actual product that is

delivered (Schils *et al.*, 2018; Senepati and Semenov, 2019). In terms of the development of new cultivars, there are inherent challenges in incorporating multiple climate risk factors into genotypes and ideotypes because gene selection to reduce one type of risk may exacerbate another risk. Research suggests that for years with favourable weather, optimal adaptation (notably improved N-use efficiency) on some farms could lead to wheat yields reaching 20t/ha (Mitchell and Sheehy, 2018), although there are significant barriers to achieving this in the wider sector (see below).

Unfortunately, practitioner surveys remain irregular, making it difficult to draw firm conclusions on trends relating to adaptation in agriculture. However, the information available (Defra and AHDB surveys etc.) suggests that although some forms of adaptation may be increasing, such as those related to water resources and flooding, this is often triggered as a response to specific events, and in general that adaptation remains rather patchy and sporadic rather than as a component of a longer-term strategy.

Defra Farm Business Surveys show that the percentage of farm businesses using different water sources has stayed relatively similar (up to 2015-16), with some further details also available from AHDB surveys (ADAS, 2019). An AHDB survey of farmers indicated that most irrigation water continues to be sourced from groundwater (ca. 30 million m<sup>3</sup>) compared to surface water (ca. 15 million m<sup>3</sup>) with very little provided by alternative supplies such as harvested rainwater. The same AHDB survey showed that about 67% of respondents had some form of water storage (reservoir, tank or rainwater harvesting) and about 65% use specialist irrigation scheduling software, with soil/substrate moisture monitoring, timing systems, or humidity/evapotranspiration sensors also frequently used. The mostly commonly used water efficiency measures were night irrigation, improved monitoring and scheduling of crop water use, installing new irrigation technologies/systems, and prioritising irrigation of different crops. Lesser used actions included trading water with other users, adjusted abstraction periods/extended licences, installing rainwater harvesting/recycling, and applying voluntary restrictions during shortages. Currently, about 35% of the volume of water licensed for spray irrigation is identified as drawn from winter storage and this proportion is steadily increasing.

Similarly, in livestock farming, the available evidence suggests that most responses are mainly reactive and short-term adjustments rather than long-term decisions. For example, analysis following the 2018 drought in England found that responses were mainly focussed on coping strategies to address feeding shortages with much less emphasis on changes in land use or farm management to enhance fodder resilience against future droughts (Salmoral *et al.*, 2020).

In forestry, the British Woodland Survey 2020 (BWS2020: Hemery *et al.*, 2020) identified a high proportion of respondents were strongly motivated to diversify tree species for biodiversity (median value 9 out of 10), ecosystem services (median value 7/10), or carbon (median value 5/10), but that, for those owners with available land, lack of grant aid or the complexity of the grant/regulatory scheme acted against expansion of woodland cover. Previous surveys have also indicated that production goals are typically the main reason acting against species diversification. Stakeholder perceptions are obviously strongly influenced by personal experience and a preference for those species that are assumed to be more productive based upon past performance may neglect new factors (e.g., pests and pathogens for forestry – Risk N8) that could imply a stronger case for

diversification. Knowledge exchange and outreach associated with new species trials and demonstration plots or stands can therefore have a valuable role in updating risk perceptions. BWS2020 found that most respondent woodland owners (69%) did not have a UKFS compliant management plan in place. Whilst concerns have been expressed about the sector and geographic representativeness of the BWS, the lack of other comprehensive surveys means that it continues to be an important source for adaptation progress. Evidence from specific locations in the UK suggests adaptation remains limited in the private sector (Lawrence and Marzano, 2014).

Practitioner networks provide an important route for knowledge exchange both in agriculture and forestry, and in some cases linked with accreditation schemes to provide quality assurance (e.g., LEAF). In addition, the Nature Friendly Farming Network (NFFN) is an example of farmer-led movement interested in improved climate change responses, although its current emphasis has been on reducing GHG emissions.

### 3.7.2.3 Barriers preventing adaptation (N6)

Several recent reports have identified barriers to proactive actions in the land sector which include: path dependency and inertia in land use decision-making (many reasons, often cultural); previous confusion on target outcomes between different policy initiatives; challenges related to insecure land tenure; mismatch between grant incentives, markets, and the longer-term requirements of both climate change adaptation and mitigation (eg. RSA, 2020; CCC 2018b). In addition, there are well-known cultural differences between agriculture and forestry meaning that these land uses are not usually considered together, resulting in a fragmented approach to land use decisions, and often that forestry is pushed to the more marginal land (e.g., Brown, 2020). In addition, limited use of near-term climate forecasts (seasonal to decadal) as well as longer-term climate projections continues to be a feature of agricultural decision-making and crop breeding (Falloon *et al.*, 2014; Falloon *et al.*, 2015), although there has been greater uptake within forestry.

Despite potential multiple benefits (including for reduced soil erosion and nutrient runoff, shelter for livestock, and carbon storage), agroforestry remains very underdeveloped as a land use option in the UK with only 3.25% (549,600 ha) of total agricultural land under agroforestry use, almost all of it in silvo-pastoral systems (den Herder *et al.*, 2017). Only ca. 2,000 ha of land is in silvo-arable use, mainly in England and Wales. The reason for this appears to be primarily related to the assumed loss of productivity by farmers.

In agriculture, government has usually acted to provide grants to farmers to cover losses from extreme events. Insurance cover is available in the private market, but often limited due to the potential for catastrophic losses, and the problems of adverse selection and moral hazard, and uptake remains limited especially amongst smaller farmers. Full multi-hazard crop insurance across the sector is generally only considered viable with government backing, with the private sector as administrator, but this may also be due to the considerable inertia in the sector previously noted.

Investment in new infrastructure or machinery to improve production efficiency or environmental outcomes can also be a barrier. Many irrigated holdings are constrained by the capacity of their

irrigation infrastructure meaning they have an effective design limit equivalent to an evapotranspiration rate of 2.5 mm/day on average (Gadankis *et al.*, 2015), yet this can be exceeded during current drought periods (e.g., summer 2018) and expected to be considerably exceeded by the increase in future evapotranspiration rates in future (ca. 4-5 mm/day by the 2050s under a central UKCP18 projection). This limitation may be alleviated by increased use of on-farm storage to take advantage of increased winter rainfall, but again this requires further investment and capital costs can be significant.

In forestry, information from the British Woodland Survey 2020 and previous surveys suggests that awareness of the range of impacts from climate change is increasing. However, planned adaptation actions to reduce risks remains limited (Hemery *et al.*, 2020), and stakeholder interviews suggest that future uncertainty, including as communicated through climate projections, remains a significant barrier (Lawrence and Marzano, 2014)

As highlighted in the chapter Introduction (Box 3.1), management of wildfire risks, although evolving, is sometimes fragmented amongst multiple organisations and strategies are yet to fully incorporate climate change (Gazzard *et al.*, 2016).

#### 3.7.2.4 Adaptation shortfall (N6)

Despite recent policy developments, there is no clear evidence that climate risks or opportunities are being successfully managed, nor is there yet a dedicated plan or strategy in place to support this process for any of the UK nations. Strategic planning is more in evidence for the forestry sector compared to agriculture, but much of the impetus of this is provided by climate change mitigation (especially Net Zero) rather than climate change adaptation, although adaptation guidance is now being enhanced. As identified above, the presence of significant barriers in the land sector means that there is a known disjunct between policy aspiration and the reality on the ground, and our assessment identifies that this remains as a major problem.

A further significant challenge is that there is as yet no long-term integrated policy for changes in strategic land allocation that integrates agricultural and forestry production together with other land use objectives in the context of climate change (adaptation and mitigation). For example, the recent RSA (2020) report on the future of the land identified a strong need for a more coherent land use strategy for the UK, and the Food, Farming and Countryside Commission (2021) have recommended a place-based national land use framework for England. Although Scotland has pioneered an integrated approach through the Land Use Strategy, this has not yet been translated into spatial planning guidelines and targeted measures that both maintain production capability and deliver other land use objectives in the context of climate change. Similarly, in Northern Ireland, the proposed Sustainable Land Management Strategy (Expert Working Group, 2020) provides a thorough diagnosis of existing problems and a vision for a more sustainable future, but as yet is only at the visioning stage and has not been translated into actions on the ground. In Wales, an enhanced evidence base is being provided through the CSCP research initiative and the next stages will involve this being translated into policy implementation guidance documents.

We therefore assess there to be a significant adaptation shortfall for England, Scotland, Wales and Northern Ireland regarding management of this risk and opportunity. This assessment has only low confidence because evidence on adaptation outcomes remains very limited although the patchy evidence for adaptation taking place on the ground should be cause for concern in itself, especially for agriculture. Whilst there are developments in national policies that have the potential to significantly address the gap, these remain in progress and current action is not sufficient to manage the future levels of risks down to low magnitude levels. This should be of especial concern because of policy aspirations to increase the proportion of domestic production as compared to international sources.

### 3.7.2.5 Adaptation Scores (N6)

<b>Table 3.20</b> Adaptation scores for risks to and opportunities for agricultural and forestry productivity from extreme events and changing climatic conditions (including temperature change, water scarcity, wildfire, flooding, coastal erosion, wind)			
<b>Are the risks and opportunities going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Very Partially* (Low confidence)	No (Low confidence)	Very Partially* (Low confidence)	Very Partially* (Low confidence)

\* Primarily for forestry production in the public sector, although goals are more multifunctional

### 3.7.3 Benefits of further adaptation action in the next five years (N6)

Different types of benefits from further actions are summarised below:

#### 3.7.3.1 Skills, training and knowledge (N6)

CCC (2020) identified that government should develop an effective strategy to address the historical productivity gap in UK agriculture including: skills, training and knowledge exchange; rural infrastructure and connectivity; and delivering R&D at farm level. The shortfall identified in this CCRA report provides further support for such a development. A major impetus for this strategy should be to better link adaptation and mitigation across the land use sector as a whole including combined pathway(s) to achieve the 2045/2050 Net Zero outcome whilst also delivering on sustainable production and environmental quality goals. There should also be considerable benefits from extending such a strategy across the land use sector as a whole, and especially in integrating developments in both agriculture and forestry together more effectively, both for production and wider environmental goals.

#### 3.7.3.2 Managing synergies and trade-offs between climate change mitigation and adaptation (N6)

From an adaptation perspective, managing risk and uncertainty suggests the need for increased diversity in cropping systems and across different land uses which may conflict with the assumed land optimisation agenda for Net Zero. However, there are also considerable synergies that can be delivered in improved use and management of land to deliver combined production and Net Zero

goals whilst also aiming to avoid negative externalities (e.g., low carbon farming; improved N-use efficiency; enhanced soil quality measures; water resources and flood management). A notable example would be schemes to increase uptake of N-fixing crops and forages, both in arable crop rotations and in permanent pastures, as supported by knowledge exchange and guidance on the combined adaptation/mitigation benefits. Another example would be increased adoption of schemes to improve soil quality, including use of no-till farming to enhance soil carbon and provide benefits (Cooper *et al.*, 2021), and measures to avoid soil compaction (Chamen *et al.*, 2015), both of which have been shown to have co-benefits for maintaining yields and productivity over the longer term.

The CCC (2020) Net Zero pathways identify the need to sustainably increase crop productivity and livestock grazing intensity in order to make additional space for woodland expansion and bioenergy crops on former agricultural land. The challenge is therefore how to achieve this in a changing climate on suitable land that does not introduce additional risks. For example, the CCC (2020) Net Zero balanced scenario assumes that average planting rates of miscanthus, short rotation coppice and short rotation forestry scale up to 23,000 hectares per year from the mid-2020s. Currently perennial energy crops made up just 0.2% of UK arable areas, while short rotation forestry (SRF) for bioenergy is virtually non-existent. This therefore implies major land use change over a few years and at a scale not previously seen in Britain on this timescale, and to meet sustainability criteria will require investment in a much stronger evidence base to ensure that it is consistent with the changing climate risks described in this CCRA.

An alternative approach to reach Net Zero has been outlined by the Food, Farming and Countryside Commission (2021) based upon agroecological principles and a return to mixed farming systems (cropping, livestock and agroforestry) throughout the UK. It would also involve re-establishment of more arable in the western UK regions and more pasture in the east. This strategic vision also remains largely untested from a climate change adaptation perspective, notably the implications from expected lower and less volatile annual crop yields and putative advantages for biodiversity, soil and water quality, and landscape character etc. Important insights may therefore be obtained by contrasting this approach with the CCC (2020) Net Zero pathways, especially across scales, regarding transition to an integrated spatial strategy to maximise delivery of Net Zero together with adaptation outcomes.

The role of policy reform, including current developments such as ELM and equivalents in the DAs, will be crucial in maximising such synergies, especially with Net Zero objectives. This should therefore seek to avert the negative distorting effects that have occurred previously when goals have been defined in isolation without consideration of side-effects or local contexts. For example, the provision for local-scale and landscape-scale schemes in ELM can provide this framework, although presently details for their implementation remain to be established. In this context, a key component of policy reform will therefore be suitable indicators that provide a more holistic measure of desired land management outcomes as related to long-term sustainability.

### 3.7.3.3 Integrated soil and water management (N6)

A range of potential mechanisms have been identified that may allow adaptation of irrigation-fed farming (Rey *et al.*, 2017), either to better manage demand through improved irrigation efficiency or

prioritising high value crops, or to enhance supply such as by increased use of water storage. For example, a survey of 66 horticultural farms in England found that on average, water requirements could be reduced by 35% to achieve the same output (gross margin) (Gadankis *et al.*, 2015). In addition, reform of regulatory arrangements such as water sharing and water trading with reallocation of unused licenses, can have beneficial outcomes, as has been further developed in other countries.

Furthermore, additional adaptation responses for addressing agricultural drought can include:

- shifting to earlier planting to avoid coincidence of high drought risk with most sensitive growth stages.
- selecting more drought tolerant crops and varieties, including those with deeper rooting characteristics or other advantageous traits.
- enhanced soil management responses to enhance water retention such as reduced or no-tillage systems, or organic amendments, and enhanced infiltration.

There are likely to be considerable benefits from further trialling and implementation of such responses in drought-sensitive areas, including further refinement to match with local land use contexts.

For forestry, as discussed in further detail with regard to pests and pathogens in Risk N8, but equally applicable to drought risk, there may be important advantages from further consideration of schemes to enhance genetic adaptability of key species, in addition to species diversification (Whittet *et al.*, 2019). This could include increased use of drought-resistant varieties (e.g., from warmer, more southerly locations) in the provenance of seed stock.

Improved awareness and understanding of adaptation options, which in the present situation and especially for agriculture shows a strong path dependency effect based upon continuation of past decisions, could be enhanced through improved availability and communication of monitoring (especially taking advantage of latest developments in remote sensing). This is especially applicable to soil moisture monitoring as the key variable linking drought and wetness risk to plant growth, together with further research to develop indices and indicators that can communicate changing risk levels to land managers in a practical context (Haro-Monteagudo *et al.*, 2018; Parsons *et al.*, 2019).

#### 3.7.3.4 Flood risk management (N6)

The benefits of additional action over and above what is planned is shown by the Enhanced Adaptation option investigated by Sayers *et al.* (2020) which investigated further adaptation for flood risk management in the context of increased implementation of managed coastal realignment (MCR) and natural flood management (NFM). Managed realignment is one of four options available to coastal local authorities through Shoreline Management Plans (SMPs) to manage local circumstances (see Risk N17).

As shown by Table 3.21, and by comparison against a continuation of existing adaptation (Table 3.19 above), it can be seen that although there is a small additional reduction in flood risk for some locations there are also anomalies where there is an increased area of existing high-quality land at risk which is due to the assumed implementation of MCR/NFM. This analysis is therefore beginning to highlight the complex adaptation trade-offs that will occur from loss of existing farmland and its production value when compared against the other benefits that may be gained from its strategic use to manage flood risk. In either case, it would generally be assumed that the most productive land (i.e., BMV or PAL) would be protected as a strategic resource unless prohibitively expensive to maintain an appropriate level of flood protection (which may include increased use of lesser quality of land elsewhere in the catchment or coastal zone as the flood alleviation zone).

**Table 3.21.** Changes in land at significant risk of flooding (frequency of 1 in 75 year or greater) due to an extended ambition for adaptation policies (i) coastal (ii) fluvial. Source: Sayers et al., (2020)

i) Coastal					
Assets at significant risk	Baseline (Ha)	2050s on a pathway to +2°C in 2100	2080s on a pathway to +2°C in 2100	2050s on a pathway to +4°C in 2100	2080s on a pathway to +4°C in 2100
BMV land England	68,796	57%	74%	73%	97%
PAL Scotland	11,082	5%	8%	9%	14%
BMV land Wales	10,726	21%	38%	37%	66%
BMV land N. Ireland	65	0%	0%	0%	0%
ii) Fluvial					
Assets at significant risk	Baseline (Ha)	2050s on a pathway to +2°C in 2100	2080s on a pathway to +2°C in 2100	2050s on a pathway to +4°C in 2100	2080s on a pathway to +4°C in 2100
BMV land England	259,248	22%	17%	23%	23%
PAL Scotland	90,727	26%	32%	38%	49%
BMV land Wales	52,413	47%	45%	58%	69%
BMV land N. Ireland	3,442	11%	30%	50%	68%

Partnership funding schemes now aim to take loss of agricultural production into their calculations. In England, the new government flood and coastal erosion risk management policy statement and associated National Flood and Coastal Erosion Management Strategy, both published in 2020



represent an enhanced adaptation commitment. Analysis has not yet indicated how the level of risk management compare with the Enhanced Adaptation option in the Sayers et al. (2020) study which used a different set of assumptions than those set out in the new policy statement and management strategy for England.

#### 3.7.3.5 Encouraging innovation and diversification (N6)

As recognised in section 3.7.2.5, there are also underlying socioeconomic barriers to be addressed in order to facilitate a more proactive and integrated approach to adaptation decision making amongst land managers, including security of land tenure, access to new technology, and divergent cultures between agriculture and forestry interests. This may require new approaches to risk sharing and further schemes to encourage innovation, including new enterprises and entrants. In addition, the identified challenges for production identify an increased need to establish more resilient supply chains, and especially to maximise enhanced opportunities for local food production including potentially new or novel crops for specific locations (see also Risk N9).

Analysis in forestry has shown the type of management strategy can have a strong influence on the future provision of forest ecosystem goods and services (timber production, standing biomass, and biodiversity index: Ray *et al.*, 2019). This analysis investigated alternative diversification and prioritisation strategies to business as usual, including different species and silviculture systems (increased short-rotation forestry or continuous cover forestry etc.) based upon relationship to a single climate projection from the HadRM3 climate model ensemble that was assumed equivalent to the RCP4.5 scenario. Dothistroma needle blight could reduce standing biomass (by up to 3 t/ha) and timber volume (by up to 5 m<sup>3</sup>/ha) dependent on management system. Diversifications, as represented notably by a broadleaved species management priority or other ‘selected species’ priority, were shown to improve standing biomass and biodiversity, but slightly reduce timber volume in all scenarios. In some key locations, such as North Highland and Moray & Aberdeen, changes in species selection and silvicultural management could improve biomass provision, timber production, and biodiversity whilst reducing Dothistroma risk, potentially providing a win-win outcome.

A key challenge, especially for agriculture and horticulture, is that climate change inevitably will involve increased unpredictability of risk, even with ongoing improvements in forecasting systems. However, although farm and land use diversification provide a means to accommodate this unpredictability, this potentially has a trade-off with economic performance and is counter to trends towards farm specialisation over recent decades. Diversification would therefore require policy support, including options based upon grants, tax breaks, legislative enablers, and mechanisms for collective action, in order to enhance adaptive capacity for this trajectory.

#### 3.7.3.6 Research (N6)

There are also important evidence gaps for this risk topic and addressing these would also improve targeting of adaptation measures based upon key climate sensitivities. These knowledge gaps remain especially notable for grassland and livestock systems where, despite recent improvements, evidence is still somewhat limited regarding linkages between impacts and adaptation responses

across the wide diversity of livestock systems that occur throughout the UK. General reviews of evidence (e.g. Rojas-Downing *et al.*, 2017; Wreford and Topp, 2020) have highlighted a range of adaptation options, included improved grazing management (timing, plant species etc.), genetic improvements, nutritional and diet management, infrastructure changes, and enhanced responses to pests and pathogens (see also Risk N7), but these need further refinement in the UK context and also to take better account of concurrent activities to improve the efficiency of livestock production to meet Net Zero targets.

In addition, although ‘sustainable intensification’ is an important focus of current research agendas, there is presently limited inclusion of adaptation in these programmes. In this context, evidence suggesting that landscape configuration, especially inclusion of semi-natural habitats together with farmland, has benefits for yield stability (Pywell *et al.*, 2015; Redhead *et al.*, 2021), deserves further detailed investigation in a range of different contexts as a prospective key adaptation strategy.

#### 3.7.3.7 Coordination (N6)

As identified above, risks and opportunities for agricultural and forestry productivity have important interactions with other CCRA chapters and show the potentially pivotal importance of this issue for rural communities. This identifies the need for better coordinated actions between government and the land use sector in terms of both enhanced productivity but also protection of natural resources (water, soil, biodiversity, land etc.) on which productivity depends. In terms of adaptation planning, there are critical decisions to be made on the long-term sustainability of some types and modes of production in their current locations, and in some cases whether investment should be moved towards new areas that are likely to be more climate resilient in the longer term (especially on the context of water availability). This challenge emphasises the importance of also recognising that agriculture and forestry enterprises are businesses and that adaptation is also strongly dependent on key adaptation issues in a business context, such as access to capital (including government grants or subsidies), availability of new skills and knowledge, networking and business security (this will also involve further developments in associated initiatives, such as insurance (see Chapter 6: Surminski, 2021).

#### 3.7.3.8 Indicative costs and benefits of additional adaptation (N6)

There are a number of studies on costs and benefits of adaptation actions (Watkiss and Hunt, 2018), although their conclusions depend on the modelling approach (i.e., whether using farm level analysis, crop models, econometric analysis, or partial or general equilibrium models). Early studies using crop productivity models tend to identify increased use of irrigation and fertiliser to address changing yields, but rarely covered potential limits (e.g., water availability or implications of fertiliser use). Another series of models use partial or general equilibrium models to analysis adaptation options including trade, shifting crop types and land-use expansion. These highlight important issues of market driven adaptation, and that changes that occur from impacts in the UK need to be seen in the European and even global context. Such studies (e.g., Hristov *et al.*, 2020) report that large negative climate change impacts on productivity outside of the EU can lead to large market spill-over effects which could push up production in Northern Europe (including the UK, and assuming

production capacity is available) as higher demand for some agricultural commodities outside of EU results in higher producer prices.

At local level, economic studies have found a large number of no- and low-regret options including agronomic options such as changing sowing dates, planting new cultivars or varieties, or changing management practices (Watkiss and Hunt, 2018). These are often already implemented as reactive or even planned measures by farmers as adjustments to weather and climate variability, however effectiveness is usually highly variable depending on the context for the measure and differs for crops and regions. As discussed in previous CCRA, more strategic options that have good benefit to cost ratios include increasing water supply through on-farm storage reservoirs and incentivising efficient water management, the introduction and increasing expenditures on research and development (Wreford and Renwick, 2012; Moran *et al.*, 2013; Frontier Economics, 2013). In addition, studies also support early options that focus on enhancing adaptive capacity through research, awareness, information provision, best practice and addressing barriers. This may be complemented by further investment in weather and climate services (seasonal forecasting etc.) to improve the quality of information on climate sensitivity and further support for technological developments, notably precision agriculture.

In particular, and highlighting the risks transferred from the land use sector to biodiversity, soils and water (see Risks N1, N4, N11), there is enhanced policy interest in 'climate-smart' initiatives, although here additional policy support will likely be crucial, as through agri-environment scheme payments. For agriculture, direct benefits from improved environmental protection for farm incomes (rather than society as a whole) generally take longer to accrue and include non-market and off-site benefits. For individual practices, benefit to cost ratios are often highly site-specific, with varied evidence on practices as viable standalone adaptation strategies (e.g., Kuhlman *et al.*, 2010). Previous qualitative economic appraisal by Frontier Economics (2013) found UK farming uptake of soil protection measures was relatively low, partly influenced by awareness but also financial return.

A report commissioned by the CCC from AECOM (2018) examined how taking a long-term approach to considering the risks from climate change, and anticipating land-use changes to manage these risks, could deliver net benefits in terms of the maintenance of natural capital and the services it provides. An 'adaptation pathways' approach was used to develop understanding of how the need for planned transformational change can be understood and analysed. Four case study locations were scoped for the research all of which had agriculture as a significant proportion of existing land use: Norfolk and Suffolk Broads; Somerset; the Petteril; and Moor House and Upper Teesdale. The case studies showed that in scenarios where future climate change presents a threat to current land uses, the use of adaptation pathways that consider land-use change in advance of the climate hazard event occurring deliver higher net benefits compared to waiting until the hazard has occurred. Assuming anticipatory action was taken, it was shown to hypothetically improve total net benefits over and above a business-as-usual scenario by between £2,500 per ha and £8,400 per ha across the four English case study locations analysed in report.

Posthumus *et al.* (2015), using an ecosystem services valuation approach, found that for soil erosion, use of tramline management, mulching, buffer strips, high-density planting and sediment traps were the most cost-effective control measures, with contour ploughing also cost-effective in some circumstances. However, as above, the study also found that assessments of effectiveness really

need to be made at farm level or field level, because of the wide variation in biophysical and land use contexts, emphasising again the key role of outreach and guidance in stimulating proactive adaptation actions on the ground. SRUC (2013) for the CCC also looked at soil management, considering six adaptations on a number of different crops. Under these assumptions, all the adaptations analysed (with one exception, for cover crops) generated positive NPVs. These did not require long lead times and had positive ancillary benefits, but the study still identified the challenge would be to encourage farmers to adopt them. All of this suggests that while sustainable soil management approaches have potential for reducing climate impacts, their uptake requires these barriers to be addressed, and may need a combination of awareness and incentives to realise (Watkiss *et al.*, 2019) though there are obvious opportunities to provide additional incentives through revision of the current farm payment schemes.

Livestock adaptation options have been evaluated by Dittrich *et al.* (2017). The costs involved in adapting the farming system range from simple low- or no-cost to those requiring large investments of capital and labour (Wreford *et al.*, 2015; Wreford and Topp, 2020). The lead-time and lifetime of that adaptation measure influence the choice of economic appraisal method used for the evaluation (Dittrich *et al.*, 2017). In the case of short-term decisions that require a small investment or a reversible action, cost-benefit analysis (CBA) is appropriate. On the other hand, projects that have a longer lead-time or long lifetimes require methods that incorporate uncertainty (Dittrich *et al.*, 2017). Thus, when farmers consider changing the composition of the dairy herd to maximise productivity and minimise stress, portfolio analysis, which evaluates several options in terms of herd structure, is appropriate. However, when the impact on the farmer relates to the frequency of extreme events, real option appraisal can be used as it allows for learning over time, and this method may be more suited to natural flood risk management measures to protect livestock and agricultural land, and housing to protect animals from heat.

Studies on adaptation costs and benefits in relation to sustainable forestry management investigate the challenges in making long-term decisions over individual or multiple rotation cycles. Increasingly these show the advantages from moving to a more diversified system rather than monocultures as developed in the past, as also consistent also with the general shift towards multifunctional forestry, including the increasing present and future threats from pests, pathogens and INNS (Risk N8) (e.g., Ray *et al.*, 2019).

### 3.7.3.9. Overall urgency scores (N6)

**Table 3.22** Urgency scores for risks to and opportunities for agricultural and forestry productivity from extreme events and changing climatic conditions (including temperature change, water scarcity, wildfire, flooding, coastal erosion, wind)

Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	More action needed	More action needed	More action needed
Confidence	Medium	Medium	Medium	Medium

Given the potentially high levels of future risk across the UK, together with a significant gap in adaptation sufficient to manage this risk down to a low level by 2100, particularly for agriculture, 'more action needed' urgency scores have been assigned to England, Wales, Scotland and Northern Ireland. The urgency is further underscored by the usual long lead times between policy initiatives and effective action on the ground for the land use sector, including challenges in overcoming decision inertia and high potential for lock-in to an unsustainable future.

More action is especially required to match land uses with the best use of the land in terms of capability to provide different functions and services, notably productive capacity in the context of this specific risk, but also recognising the importance of other land use functions and ecosystem services (soil quality, water quality, flood risk alleviation, carbon storage etc.). This will require a more integrated approach to strategic land-use planning bringing together both climate change adaptation and mitigation. In addition, as described above, addressing threats to productivity requires a supporting policy framework to improve knowledge exchange, encourage innovation, and address underlying socioeconomic issues (e.g., land tenure; sector demographics etc.).

### 3.7.4 Looking ahead (N6)

The following would be useful to provide an improved assessment capability in CCRA4:

- Regular systematic survey on the uptake of adaptation practices in the UK, including for different farming/forestry systems and locations, and integration with related land use datasets such as the National Forestry Inventory or agricultural census data.
- Application and trialling of near-term climate forecasts as related to productivity issues.
- Climate information tailored to crop breeding programmes (see also Risk N9).
- A more comprehensive assessment of climate resilience and robustness of different land use options in the context of changing water availability, including risks and opportunities for both rainfed and irrigated farming systems.
- Address key knowledge gaps – e.g., grasslands (see agenda of Kipling *et al.*, 2016).
- Better integration of adaptation pathways with Net Zero pathways.
- Combined use of climate projections with socioeconomic scenarios to place UK domestic production in an international context.

## 3.8. Risks to agriculture from pests, pathogens, and INNS (N7)

- Pests, pathogens and invasive non-native species present serious risks to agricultural productivity, with consequences for livelihoods and businesses. Large-scale outbreaks or invasions may also have ramifications for food security.
- The combined risk factors (climate and non-climate) clearly suggest that the magnitude of this risk is increasing from medium (present) to high (future).
- Current institutional risk assessment procedures provide some adaptive capacity that acts to reduce the risk to a lower level at present and this will also have benefits in reducing risk in the future.

- There is a need for additional urgent action to improve preparedness, including improved surveillance, especially in the context of the need for enhanced international co-ordination following EU-exit and associated trade agreements.
- The role of Integrated Pest Management (IPM) should be further supported in an adaptation context to help avoid the various negative consequences of excessive pesticide use.

## Introduction

Although originally defined separately for this CCRA, risks to agriculture from pests, pathogen and invasive non-native species (INNS; see Glossary for definitions) have been combined together because climate change tends to blur the distinctions (e.g., some INNS are vectors for pathogens) and adaptation requires an integrated approach to biosecurity and surveillance.

The relationship of this risk with both climate and climate change is multi-faceted. Each problem species or micro-organism has its own specific climate sensitivities that can favour their increased incidence. This includes parameters related to maximum and minimum temperature, moisture (both precipitation and specific/relative humidity can have an influence), and potentially wind (notably direction); these typically act in combination and also are related to their duration or frequency. In addition, socioeconomic factors are highly influential, including both management factors at farm level and large-scale drivers such as trends towards globalisation of trade and travel.

The combined risk factors (climate and non-climate) clearly suggest that the magnitude of this risk is increasing, despite ongoing scientific challenges in attributing the relative influence of individual risk factors. In aggregate, across the range of known risks (only a limited set of which have been currently quantified), we assess this risk as increasing from medium (present) to high (future) based upon expert opinion, with the risk magnitude also being proportional to the degree of climate change. We also recognise limits on our knowledge of this climate risk relationship, more notably because the most severe outbreaks are typically related to extreme or anomalous climate conditions.

The current institutional risk assessment procedures provide some adaptive capacity that acts to reduce the residual risk to a lower level at present and this will also have benefits in reducing residual risks in the future. However, future climate change, especially in a world with a higher magnitude of climate change, will almost certainly bring new risks that challenge current procedures. There is therefore scope for additional urgent action to improve preparedness, including enhanced surveillance and horizon scanning, and to address the increased prospect of emergent risks (especially from novel pathogens) through additional contingency planning. The timing of emergent risks is especially uncertain; therefore, contingency planning can have benefits even for the present-day.

It is very likely that EU-exit will have important implications for this risk through modified trade arrangements and associated adjustments to regulatory regimes, but details on these changes remain very limited at present. In addition, we have very limited information on how COVID-19 may modify this risk beyond a general increased public awareness of the severe consequences that arise from spread of pathogens.

### 3.8.1 Current and future level of risk (N7)

#### 3.8.1.1 Current risk (N7)

There are important uncertainties regarding the changing incidence of pests, pathogens and INNS (see below), although the evidence is at least strong enough to establish that the magnitude of their combined risk is already a significant challenge for the agriculture sector. In addition to academic publications, evidence is provided by current status of pest risk assessments, together with similar assessments for pathogens and INNS, which in many cases identify climate as a contributing risk factor. Nevertheless, in terms of an aggregated assessment in our view the evidence remains incomplete and heavily based upon specific examples rather than a more complete assessment of the overall risk.

The risk from pathogens has been conceptualised in terms of a disease triangle (Fones *et al.*, 2020), involving the interaction of host presence/susceptibility (including factors such as genetic resistance and plant health), pathogen virulence (factors such as population size, genes, sporulation, lifecycle and selection pressures), and environmental factors (temperature, humidity, light, soil nutrients, air pollution). Climate factors have been particularly highlighted with regard to the changing incidence of some crop diseases. For example, ADAS (2019) analysed septoria and yellow rust in winter wheat with the aim of developing a climate change indicator and found large interannual variability in disease incidence which appears to be linked with variable weather conditions, with septoria peaking in 2012, 2016 and 2017, and yellow rust peaking in 2014 and 2016. Field trial data also indicates that during these peak years, untreated crops had significant lower yield than treated crops (typically 3.6 t/ha compared to 5 t/ha), which demonstrates the negative impacts that disease outbreaks can have on agricultural production (in combination with other factors already identified for Risk N6). These impacts can incur large damages for the sector: for example, the greatest threat at present for the wheat crop is *Septoria tritici blotch* (STB), which is dispersed by wind-blown spores and, based upon assumed 5-10% harvest losses has been estimated in an EU study to cost UK growers alone around €120-240m per year in yield losses (Fones and Gurr, 2015).

Regarding pathogens in livestock, considerable emphasis has been placed recently on the risk of Bluetongue virus which affects cattle/sheep and is spread by the bites of midges (*Culicoides* species), acting as a vector. Transmission has been linked to the influence of higher temperatures in accelerating the midge lifecycle, abundance, and range, and hence virus development (Jacquot *et al.*, 2017). Outbreaks are most frequent in late summer when midge populations peak. An outbreak in the UK in 2007 was linked to prevailing southerly winds from France (Jones *et al.*, 2019), and the virus has also been detected in cattle imported from France into the UK. Outbreaks in other European countries have resulted in severe economic impacts (e.g., Gethmann *et al.*, 2020).

Much of the southeast UK already has suitable temperatures for bluetongue transmission, but suitability is currently at a lesser level for areas further north and west. Analysis at 10 farm sites in southern Ireland has shown that *Culicoides* abundance was highly correlated with ambient temperatures in the region, and the species responsible for both Bluetongue transmission and the more recent risk from Schmallenberg disease (SBV) were present (Collins *et al.*, 2018). Wind patterns are an important factor in assessing risks through *Culicoides* redistribution, and hence may transport pathogens from continental Europe to the UK or southern Ireland to Northern Ireland. For example, it has been proposed that the re-emergence of SBV in Ireland in 2016 was a result of favourable

easterly wind conditions that could have facilitated the transport of virus-infected *Culicoides* into Ireland from neighbouring countries (Collins *et al.*, 2017).

Socioeconomic factors interact with climate factors to also influence the magnitude of risk, most notably at macro-scale through globalisation and the changing pattern of trade. At farm or landscape scale, management factors can also have a key influence. Analysis for the UK Plant Health Risk Register has highlighted inherent vulnerabilities related to current methods of production. For example, the impetus to maximise crop yields has in some cases meant a preference for one dominant variety/cultivar or only a small range of varieties/cultivars. Hence, if this selection becomes susceptible to certain pests or pathogens, then there is limited capacity for a fallback to more resistant types.

The emergent risk from new pathogens is of particular concern. An example of such a risk in continental Europe is that now associated with a virulent but undocumented disease of kiwifruit in Italy. Currently, the exact causes of the disease remain to be established but there is a possibility that the syndrome is a physiological effect at least partially associated with another incidence of infection by *Phytophthora* species which are typically more prevalent in less aerobic, waterlogged conditions.

CCRA2 recognised the increasing climate-related risk from INNS and new evidence further demonstrates the scale of the problem. The Environmental Audit Committee (2019) report on Invasive Species identified INNS as one of the top five threats to the UK's natural environment. Previously, analysis has estimated total costs to the GB economy of £1.7 billion per year (£1.3 billion to England, £0.24 billion to Scotland and £0.13 billion to Wales) (Williams *et al.*, 2010).

In assessing risk from INNS, distinctions between introduction and establishment as compared to spread and consequent impact become important as the magnitude of impact increases at each step. Most INNS are introduced by human agency and prevailing conditions may then encourage establishment and spread. Pathways define the routes for introduction and subsequent spread. The formal international UN CBD definition of INNS emphasises human agency, but climate change acts to challenge this legal convention by modifying 'natural' species ranges. The most recent GB Non-native Species report card (2017) does recognise that a small but increasing proportion of non-natives established since 1700 have been due to 'natural movements'; in this case the risk is related to natural spread of a non-native once it has become established in a new biogeographic domain (for example, spread of harlequin ladybird or insect vectors hosting Bluetongue virus to the UK from continental Europe where it is non-native). Furthermore, the notion of a 'native' species can be challenging to apply in a consistent format, including variations across the different nations of the UK. In this assessment, we have assumed that the primary risk of a direct climate change effect on INNS is associated with natural spread and establishment from continental Europe and therefore that it will affect southern UK areas first. By contrast, an indirect climate change risk is associated with the wider group of INNS that are introduced by human agency and for which a favourable climate then further supports establishment and spread in the UK; this may occur throughout the UK and from throughout the globe (temperate Asia is a notable source of concern).

A general description of risks from INNS in the UK is provided for Risk N2 as informed by reports on existing threats from the GB Non-native Species Secretariat and horizon-scanning activities carried



out for both GB (Roy *et al.*, 2014a), Ireland (Lucy *et al.*, 2020), and Europe (Roy *et al.*, 2019) that evaluate potential threats that may materialise in the next few years.

However, the risk from damaging non-native species continues to change, requiring regular updates and refinements to risk assessments. A notable example, because of its potential to cause serious disruption to agriculture and horticulture (primarily fruit and vegetables), is the brown marmorated stink bug (*Halyomorpha halys*) which is native to Asia but spreading globally (Stoeckli *et al.*, 2020). After inadvertent introduction into Switzerland this species has been recently confirmed in south-east England although it is considered unlikely to reach more than one generation per year, which would prevent it at present from reaching harmful levels.

Evidence for risks to agriculture are especially notable when INNS are associated with damaging pathogens. For example, climate change, and especially the trend to warmer winters in recent decades, has been identified as a risk factor with regard to species such as *Candidatus Liberibacter solanacearum* (Lso) which is a pathogen primarily spread by insect vectors that can damage solanaceous crops (potato etc.) and has also been found on carrot and celery in Europe, including recently in Scotland (Sumner-Kalkun *et al.*, 2019). Similarly, for *Xylella fastidiosa* which is also a pathogenic bacterium spread by insect vectors particularly targeting vines and olives, but with potential to spread to other crops that are more common in the UK (White *et al.*, 2019).

In addition to direct impacts on agricultural production, INNS may also have indirect effects through modifying key ecosystem functions. A notable example of this is the risk to pollinators, which are essential for some crops, and already exposed to multiple pressures including from climate change and parasites (see Risk N1). Some INNS present an additional risk to pollinators, as for example with the Asian hornet which was first detected in the UK in 2016 (most probably transported through trade from China to France) (Keeling *et al.*, 2017), and because of its extensive dispersal ability has made annual incursions in England every year since. Another example would be the increased presence of the New Zealand flatworm and Australian flatworm which have now become widespread in areas within its thermal range of 0-20°C, especially in Scotland and Northern Ireland. These invasive flatworm species arrived on imported plants and prey on the native earthworms that have a key role in soil cycling, primary productivity and ecosystem functioning, with the potential for significant detrimental effects for agricultural production (Murchie and Gordon, 2013).

### 3.8.1.2 Future risk (N7)

Although knowledge has generally improved since CCRA2, investigations of climate change risks still concentrate on a few crops and pathogens. Similarly, analysis of uncertainties in crop disease models remains limited, although there is now increased use of climate model ensembles to quantify uncertainty in some crop disease projections and tools are now also being developed to explore disease dynamics at the landscape level (Newberry *et al.*, 2016).

Climate will act in combination with socio-economic drivers to determine the magnitude of risk. This includes further changes in the pattern of globalisation and trade patterns, together with the scale of active surveillance adopted and pro-active intervention to prevent dispersion of problem species or pathogens to new countries or regions. It is also likely that some patterns and types of land use

patterns, such as large-scale monocultures, may facilitate spread of some pests or pathogen vectors, due to a lack of competitors. In other cases, trends towards increased use of enclosures (e.g., polytunnels) may also be a risk factor because the modified microclimates may favour pest/pathogen increase, although with enhanced biosecurity such spaces may be able to better avoid establishment of problem species.

In general terms, the trend towards warmer and seasonally wetter conditions, most especially in winter months, is very likely to favour increased risk from some existing pests and pathogens (Stetkiewicz *et al.*, 2019). In addition, increased temperatures occurring due to climate change imply increased potential risk due to relationships with increased pathogen genetic variation and virulence, and hence for emerging pathogens (either as a new pathogen or a previously known pathogen in a new place or host), notably from fungal and oomycetes crop pathogens (Fones *et al.*, 2020).

Warmer temperatures are associated with increased over-winter survival of pest species or some pathogen vectors, and wetter, more humid conditions favour greater dispersion of many pathogens, such as *Fusarium pseudograminearum* or *Phytophthora infestans*. Other changing climatic risk factors may include increasing atmospheric CO<sub>2</sub> concentrations or changing wind regimes but evidence on these additional factors is very limited. Also, changing patterns of solar radiation can influence the spore survival viability of some pathogens, with greater radiation acting to reduce risk (e.g., *Phytophthora infestans*: Skelsey *et al.*, 2017), hence trends towards increased solar radiation in many parts of the UK as shown by UKCP18 may act to counter other climate parameters acting to increase risk. In each case, changing seasonal patterns will determine the aggregate risk in combination with the changing host plant growth cycle. For example, an increase in frequency of warm humid summers, as characterised recently by 2019 (in contrast to the warm dry summer of 2018) would imply an increased frequency of high-risk conditions for pathogens such as *Phytophthora infestans* which causes severe problems with late potato blight in the UK. Using the UKCP18 12km spatial ensemble projections, analysis has shown an increase in the warm humid conditions that are conducive to potato blight; based upon regions where most potatoes are grown at present, the 2070 risk threshold exceedance may increase by 70% in East Scotland and between 20 and 30 % across the East of England, the Midlands and Yorkshire and the Humber (RCP8.5 scenario: Garry *et al.*, 2021). Analysis by Skelsey *et al.* (2016) has also indicated that incidence of late potato blight may actually shift seasonally to increase in the first half of the growing season and decrease in the second part. Early potato blight is rarely reported at present in the UK but becoming common in Europe, hence with future projections indicating that parts of the UK will have a climate that has some of the same current climate features as continental Europe then early blight may also become of greater significance.

Whilst the life cycle of some pathogens will be enhanced by increasing temperatures, in other cases they will become more constrained, hence the future incidence of disease is likely to increasingly diverge from present-day patterns, especially at higher magnitudes of warming. For example, potato cyst nematode (PCN) species have different temperature optima for various life cycle stages which is expected to modify their distribution (Jones *et al.*, 2017). By using a PCN life cycle model guided by experimental data, risks to potato crops from three PCN populations (*Globodera pallida* (Lindley); *G. rostochiensis*; *G. pallida* (S-Fife)) have been investigated (Skelsey *et al.*, 2018). Results showed

temperature changes could result in increased survival to female maturity for all three PCN populations, with greater increases expected for Scotland, followed by Wales then England. The largest projected increases in Scotland were for *G. pallida*, whereas *G. rostochiensis* showed the largest increases in Wales and England. Implications for adaptation from this study are discussed in section 3.8.3

The changing incidence of crop disease has been recently reviewed in the context of the new data from UKCP18, with specific emphasis on Wales although the findings also often have wider applicability and will vary depending on different environments (Barrow *et al.*, 2020). Potential increases in incidence have been highlighted for yellow rust, take-all, and eyespot; in the case of eyespot, this is associated with early sowings and wetter winters, both of which are likely to increase with climate change. Warmer winters and increased winter rainfall (which also acts to limit access to the land as required for some control measures) may also increase the incidence of brown rust in wheat and of net blotch in winter barley crops, whilst the risk of rhynchosporium is likely to remain high for crops of winter and spring barley in Wales. An increase in heat stress and drought stress in summer could also have adverse impacts through increased disease outbreaks, including for ramularia. Conversely a decrease in average summer rainfall is likely to reduce the incidence of Fusarium Head Blight (Skelsey and Newton, 2015) and a possible shift to earlier sowing in autumn may reduce the risk of mildew in winter barley. For oil seed rape, diseases such as club root and Verticillium stripe may also become an increased risk, although this is another topic requiring further research.

An under-researched issue that may be associated with a further increase in risk is larger-scale patterns of crop planting across multiple farms at landscape or region-scale. This pattern of crop connectivity is a consequence of land use decisions, including the aggregated effect of autonomous responses at farm level that may encourage a larger-scale trend towards similar crops or monocultures in a region, as influenced by socio-economic factors (notably market prices for crops). In terms of the changing geographic risks of late potato blight in Scotland, these factors have been shown to have a strong influence (Skelsey *et al.*, 2016).

For livestock farming, the increased risks from parasites due to warmer, wetter winters remains a major concern, and although more evidence is becoming available there are still important knowledge gaps. CCRA2 reported on recent research showing the increased risk of fluke which prevails in wetter pastures and is likely to be an increased risk due to milder winters (with a reduced frequency of frosts that constrain fluke populations), particularly affecting livestock that remain outdoors for more of the year due to a longer growing season. *Teladorsagia circumcincta*, one of the most common and economically-damaging endemic parasites for sheep in the UK is projected to increase in a warmer climate, with Fox *et al.* (2018) inferring that the non-linear relationship with temperature could indicate that a threshold-related 'tipping point' is reached where parasite burdens abruptly increase, leading to high-intensity parasite outbreaks. Parasitic gastroenteritis is one of the most cost-effective and feasible diseases to control in Scottish sheep, but ineffective parasite control is also very likely to drive up GHG emissions from livestock (primarily methane emissions).

Changes in climate that include increased winter rainfall and high moisture levels may also exacerbate existing poor indoor ventilation within buildings, which are likely to increase the incidence of respiratory disease in housed livestock. *Haemonchus* infection of sheep was typically confined to southeast England but has recently become widespread whilst *Trichostrongylus*, which was traditionally a problem for lambs in the autumn, is now occurring earlier in the summer and persisting for longer during mild winters (Rose *et al.*, 2016; Barrow *et al.*, 2020).

Blowfly populations are a severe threat to livestock with a distinct peak in risk during the summer months. At present, the usual blowfly strike period, during which negative impacts are mostly focussed, extends from May-September, but in lowland areas when the prevailing weather is unfavourable this risk period can extend from March to December. Projections showing continued climate warming will therefore mean that this extended risk period becomes more prevalent across the UK and may even extend throughout the year in lowland locations (Rose and Wall, 2011).

Regarding bluetongue transmission, in climate projections reaching global warming of between approximately 3.2°C and 5.4°C at the end of the century<sup>19</sup>, all but the Highlands of Scotland would be warm enough for rapid spread of the virus by the 2080s (Jones *et al.*, 2019). The same analysis also found that in England and Wales, an outbreak might be expected in any year by the 2070s assuming the same RCP scenario, compared to once every 20 years now.

An additional risk factor for livestock for which we have limited evidence is the potential increase in toxic weeds. Some weed species are likely to be favoured by trends to warmer, wetter winters and this may act to limit forage quality. However, some of these species are also important in terms of their wider role in agro-ecosystems, such as for example with ragwort which is important for pollinators, therefore control of weeds will require appropriate control measures and adaptation of good practice to avoid negative side-effects.

Confidence is low for projecting future climate change risks from INNS because of the complex species-related interactions between climate change and changing socioeconomic drivers. There is an expectation of increased risk due to further developments in globalisation and world trade, but a key uncertainty is the degree to which international agreements will be universally and rigorously enforced. At higher magnitudes of climate change there is a much greater risk of new INNS becoming established in the UK and, in some cases, for emergent risks to develop as ‘unknown unknowns’ regarding the introduction of a new problem species on which we currently have a lack of knowledge, especially regarding the vulnerability of key UK crops or farm animals.

There is a high level of scientific consensus that risks from invasive species are in general expected to increase due to climate change (e.g., Bellard *et al.*, 2018; see also Risk N2). Agriculture may be especially susceptible to damage from INNS where production has favoured extensive areas of monoculture with plants favoured by the invasive species but where any natural predators have been lost therefore reducing options for control and potentially facilitating larger increases and spread of the invasive.

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<sup>19</sup> A subset of CMIP5 climate projections selected to sample the the multi-model ensemble driven by the RCP8.5 concentrations pathway. 3.2°C and 5.4°C warming represents the 5<sup>th</sup> to 95<sup>th</sup> percentile range.

As the life cycles of many INNS are especially sensitive to warming, climate suitability will expand across the UK for an increasing number of problem species. For example, Bradshaw *et al.* (2019) showed that risk from the tobacco whitefly (*Bemisia tabaci*) becoming established in the UK would be much greater in a 4°C scenario compared to a 2°C scenario (based upon inferences from the high climate change scenario RCP8.5 and CMIP5 climate models), and also with greater risk in the south of the UK compared to the north. This problem species is currently only a problem in the UK in glasshouses but is present outdoors in France. This study showed minimum temperatures in summer were a key factor determining its establishment outdoors, and with UKCP18 and CMIP5 indicating a clear trend for these to increase, this INNS can be inferred to become an increased future risk for UK cropping.

Nevertheless, more detailed projections of change in risk, such as at sub-UK level require further research. Large-scale climate modelling of the distribution of invasive species shows that there is often a lack of clear consensus on the pattern of dispersion. Although analyses of INNS are most common for plants and invertebrates, meta-analysis suggests that larger shifts may be associated with invertebrates and pathogens whereas plants and vertebrates may be more generally associated with reduced range sizes (Bellard *et al.*, 2018). Species distribution models, when validated against other data, can provide useful predictive capability for some INNS, such as the Asian hornet, indicating there is a good potential for these to be used more regularly when updating risk assessments (Barbet-Massin *et al.*, 2018).

In addition to INNS, as highlighted in previous CCRA there is also the likelihood of existing established non-native species becoming more invasive due to climate change (sometimes referred to as 'sleepers'), although there still remains very little evidence on this issue. This includes the prospect that pests may become an increasing problem in a new region or for longer periods, for example cabbage root fly in Scotland, and that changes in life cycles can introduce greater unpredictability in pest forecasts. This may result in more spraying, with consequent negative impacts on non-target species.

An additional risk factor that also needs to be considered is evolving pesticide resistance. In combination with the effects of climate change that include longer activity period and increased overwintering survival, which may produce more damaging generations for multi-voltine species, stakeholder and expert feedback into the CCRA process has indicated a shared view that pesticide resistance may become a significant risk multiplier unless alternative control strategies are available.

### 3.8.1.3 Lock-in risks (N7)

No specific lock-in risks have been identified, however, lock-in may be associated with inaction because once diseases are established (especially INNS), they are difficult and costly to eradicate, and can cause large economic costs. Hence, provided that the current risk assessment procedures remain dynamic (including continued use of horizon scanning) and are open to the possibility of changing risk factors or emergent risks then lock-in effects should be limited. This may require enhanced communication to improve awareness of changing risks, including that new introduction may have different impacts than in their native region.

#### 3.8.1.4 Potential thresholds (N7)

Climate thresholds are known to be an important factor in the establishment and spread of pests, pathogens (including vectors), and INNS, and these also define their scale and changing speed of impact. For this reason, CLIMEX-type models based upon key bioclimate metrics for individual problem species or micro-organisms are often used in risk assessments to assess changing climate exposure. In addition, some risk assessment procedures already include and are activated by known climate thresholds, such as the combination of minimum temperature and humidity for late potato blight risk (Smith periods), including more recent investigation to refine this assessment (e.g., Hutton criteria: Dancy *et al.*, 2017). Some research in Europe has already explored the use of multivariate thresholds to help understand multiple climate parameters, as for example with brown rust in wheat (temperature, humidity, and precipitation thresholds: Junk *et al.*, 2016).

As referred to above, some pathogen burden risks for livestock may have key thresholds that define a tipping point beyond which an abrupt increase in high-intensity outbreaks may occur (Fox *et al.*, 2018). For INNS, thresholds are especially relevant in understanding the initial risk of establishment, often related to minimum temperature, and for the speed and extent of spread, which can include other climate factors, although these thresholds are specific to each INNS and can also depend on other factors (e.g., land use and native biodiversity).

The CCC Thresholds study investigated the influence of higher temperatures on incidences of the sheep parasite *Haemonchus contortus*, and the implications for lamb production, using frequency of exceedance of daily mean temperature of 9 °C (Jones *et al.*, 2020). The study found that as an average across the UK the development season for this parasite increases from 171 days in the baseline period (2001 to 2010) by approximately 30 days under a 2°C scenario, and 60 days under a 4°C scenario (both derived from the high climate change scenario RCP8.5). Current average development seasons have geographic distinctions (England 179 days; Wales 164 days; Scotland 127 days; Northern Ireland 155 days) therefore there is a likelihood of greater increases in those areas which currently have a shorter season, most notably in the uplands. For the UK as a whole, baseline annual economic losses for this parasite have been estimated at £81m/year (around 7% of total production value of lamb). Under the 2°C scenario used by the Thresholds study, losses increase to £97m/year, while under the 4°C scenario they reach £113m/year which would be 10% of present lamb production value (proportionate increases are similar across each country of the UK).

#### 3.8.1.5 Cross-cutting risks and inter-dependencies (N7)

In addition to the severe implications for agricultural productivity, there are also in some cases important cross-cutting interactions with forestry, biodiversity, and human health, requiring a co-ordinated risk reduction strategy. Potential implications also occur for landscape character (Risk N18) because large-scale outbreaks can modify the visual appearance and other amenity value associated with specific land uses. Control of pests, pathogens and INNS involves important interactions also with biodiversity. For example, as previously identified, some weed species that may be agricultural pests can have wider importance, such as for pollinators (e.g., ragwort). In

addition, if control measures involve the increased use of pesticides, including new types of pesticide, there can be additional risks both to water quality and soil quality.

#### 3.8.1.6 Implications of Net Zero (N7)

The Net Zero scenario places a strong emphasis on improved productivity for crops, livestock and forestry, whilst also emphasising the importance of best management practices. However, there is presently a rather wide variation in the efficiency and effectiveness of management practices in the UK, therefore the current reality is rather distinct from an optimised scenario. Our assessment is that an over-emphasis on productivity without due regard for the need for associated good management practice, such as may occur with crop monocultures, may act to increase negative impacts when outbreaks do occur, including both for GHG emissions and wider environmental impacts (e.g., biodiversity; soil quality; water quality). Similarly, research on changing burdens of livestock parasites has shown a considerable additional potential risk to increase GHG emissions (Houdijk *et al.*, 2017; Fox *et al.*, 2018).

Further work is therefore required to assess the viability of the predicated productivity gains outlined in the Net Zero pathway in the context of an increased climate-related risk from pests, pathogens and INNS. This should also include the effects from additional deployment of risk reduction measures, as will probably be required to manage the increased climate change risk and including adaptation strategies such as modified planting periods and animal stocking schedules (indoors/outdoors etc.) together with requirements for diversification to increase overall resilience of production systems and new biosecurity systems.

#### 3.8.1.7. Inequalities (N7)

As described for Risk N6, negative impacts on production can have consequences for agricultural livelihoods, whilst also potentially affecting food availability and price in the case of the most severe outbreaks. This can potentially affect the more vulnerable groups in society. However, no specific evidence on societal inequality issues associated with climate change acting through pests, pathogens and INNS risks has yet been documented. See Risk N2 for inequalities related to risks to terrestrial habitats and species from pest, pathogens and INNS.

#### 3.8.1.8 Magnitude scores (N7)

Magnitude categories (Table 3.23) are based on expert judgement of existing/expected impacts on production outputs (guided by existing risk assessments when available) due to the limited availability of quantitative data for this topic. Confidence is low for future risks due to possibility of emergent risks although it is medium for known risks with clear climate sensitivity (e.g., fluke, Bluetongue, late potato blight). This climate sensitivity provides the rationale for elevating the risk magnitude from medium at present to high under each of the future pathways.

**Table 3.23** Magnitude scores for risks to agriculture from pests, pathogens, and INNS

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	High	High	High	High
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Medium	High	High	High	High
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Medium	High	High	High	High
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Medium	High	High	High	High
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

### 3.8.2 Extent to which current adaptation will manage the risk (N7)

#### 3.8.2.1 Effects of current adaptation policy and commitments on current and future risks (N7)

##### 3.8.2.1.1. UK-wide

The general policy context for this risk is the same as Risk N2 and therefore referenced more fully in that section, including relationships to international agreements. Established risk assessment procedures are in place for pests, pathogens, and INNS, covering both existing and new risks and including climate as a key factor. In each country, national adaptation plans provide continued support for these procedures and biosecurity measures. However, as detailed in N2 these plans cannot be regarded as fully robust because they do not define any additional measures based upon the changing risk from climate change, especially if the world were to follow a higher climate change trajectory, such as in a 4°C world. This issue is of particular concern because the likelihood of new emergent risks increases in proportion to the magnitude of climate change and may also be further exacerbated by interactions with socio-economic drivers such as further expansion of trade and globalisation of markets. Experience has indicated that emergent risks are especially notable threats



because they can challenge existing protocols that may take a lengthy period of time to re-negotiate.

The UK Plant Health Risk Register records and rates risks to UK crops, trees, gardens, and ecosystems from plant pests and pathogens, including risk mitigation and new actions to manage or reduce risk. The 2019 EU Plant Health Regulations, which include tighter controls on the import and movement of plants and plant material, have now been transposed into national law. Livestock risk assessments for known pests and pathogens (e.g., Bluetongue) are also in place. For animal pests and diseases, the Animal and Plant Health Agency (APHA), which co-ordinates activities across the UK, acts to monitor notifiable and emerging outbreaks worldwide (supported by analysis capability at the Pirbright Institute) to provide early warning, including risk of entry through trade or wildlife movements, and APHA also conduct collaborative horizon-scanning assessments and information-sharing activities internationally.

The risk assessment process is currently in transition to a new system which aims to provide both improved local information and better coordination linked to best practice guidance. This new system should include better recognition of climate change.

The 2015 Invasive Alien Species Regulation (EU) 1143/2014 has provided a regulatory framework for the prevention and management of the introduction and spread of INNS, providing a more consistent approach across countries. As required by the EU regulations, in May 2019, the UK Government published its comprehensive pathway analysis, identifying 10 priority pathways for unintentional introduction, one of these being horticultural escapes into the wider landscape. Defra has also recently commissioned research to investigate public attitudes and awareness of non-native species (Creative Research, 2018). The Invasive Alien Species (Enforcement and Permitting) Order 2019 introduces enforcement provisions, offences and penalties needed to comply with the requirements of the EU Invasive Alien Species Regulation. It gives conservation agencies and the police and border force officials new powers to address Invasive Alien Species issues in England and Wales at an early stage, and similar legislation for Scotland is now being developed.

Adaptation policies at UK level and for the DAs generally aim to further support existing procedures and ongoing research to improved information and awareness, but do not provide specific actions for agriculture. Therefore, whilst recognising the importance of the issue, the 25YEP for England and current UK NAP do not explicitly reference target outcomes for risk reduction for pests, pathogens or INNS.

Similarly, in Scotland the SCCAP2 does not include specific new actions for agriculture but does provide a commitment to continue to develop and expand the knowledge base, whilst identifying scope for a new potential indicator to record absence of INNS as complement to the current indicator on presence of INNS.

In Wales, the national adaptation plan ('Prosperity for all: A Climate Conscious Wales') emphasises the importance of existing measures and ongoing monitoring whilst also highlighting further efforts to improve awareness and guidance through the Invasive Non-Native Species (INNS) Portal. Additionally, Area Statements identify opportunities for the control of INNS, and to enable collaborative action on the ground. The Wales Animal Health and Welfare Framework aims to

address increased risks related to pests and pathogens for kept animal health (and associated public health issues) but although climate change is recognised as a key factor, the framework does not make explicit reference to specific climate change risks or adaptation actions to manage these risks.

The Northern Ireland Government assessed progress from their first Invasive Species strategy (2013) in 2017 and stated that the majority of targets within the 30 key Actions had been achieved and steady progress was being made towards non-time limited targets. In 2018 the Invasive Alien Species implementation plan was revised. The importance of ongoing biosecurity and surveillance for ensuring the vitality of the agriculture sector is also strongly recognised in Northern Ireland, although again now new measures specifically related to climate change adaptation have yet been defined.

The UK has agreed to meet international commitments to control INNS through the Bern Convention and UN CBD. The Aichi Targets, which fall under the CBD, included a commitment that by 2020 INNS and their pathways would be identified and prioritised, with priority species controlled or eradicated, and pathways managed to prevent species' introduction and establishment. However, in 2019 the UK Government has admitted that progress on meeting this target was "insufficient".

The GB Non-Native Species Secretariat (GBNNSS) coordinate work across England, Wales and Scotland, including a GB-wide strategy (latest version published in 2015) and report card (GBNNSS, 2017). Northern Ireland works on a whole-island basis for INNS with the Republic of Ireland in an All-Ireland Forum, but there are also plans for further integration into a UK Non-native Species Secretariat. Risk assessments are a key component of strategic planning and regulation, and if necessary, for legislation to reduce the risk of entry. Pathogens are not currently included within the INNS strategy, although an inquiry by the Environment Audit Committee (2019) of the UK Parliament recommended they should be included. The 25YEP for England and UK NAP has a goal and indicators related to tackling INNS through the Invasive Non-native Species Strategy. However, currently species that arrive in the UK due to climate change are not classed as 'invasive', and so are not included in the Strategy.

As identified in previous CCRAAs and by the CCC, the current definition of INNS is based upon their transfer beyond their native regions by human agency rather than when migration is assisted by a changing climate. This distinction is likely to have increasing ramifications for definition of, and actions against, INNS as they become increasingly assisted in their movements by a changing climate. A prominent example here would be the continued climate-assisted dispersion of some *Culicoides* (midge) species that can act as pathogen vectors, such as for Bluetongue disease, and which based on the current definition would not be included in current INNS policies but through animal health risk assessment.

Approaches to prevent the establishment of INNS include closing down pathways, enhancing biosecurity at ports and borders, raising public awareness and preventing secondary transfer, horizon scanning and risk assessing new threats. As an example, in 2020 strict import and movement restrictions were placed on a range of species to protect against *Xylella fastidiosa*. Since CCRA2, EU-Exit has increased uncertainties in the continued future sharing of surveillance data with EU

countries and organisations. Increasing cross-border trade has also heightened the risk of pests/pathogens entering UK through these pathways.

Work on the UK Plant Health Risk Register has highlighted inherent vulnerabilities in current production systems which are relevant to successful adaptation. For example, some UK crops are focussed on one variety, or a limited range of varieties, which reduces overall resilience because some varieties are more resistant to pests, pathogens or INNS. A prominent example here would be barley where the demands of maltsters/processors has focussed production on a few specific varieties which means there is an increased vulnerability to pests and diseases. As also emphasised below, the sector as a whole needs to develop increased awareness of the changing risks, whilst research is also continuing to enhance disease resistant traits in cultivars.

### 3.8.2.2 Effects of non-Government adaptation (N7)

Land managers and others in the supply chain have an obligation to report incidences, including for specific INNS, and therefore provide a key component of the surveillance system. However, pressures to improve production may sometimes lead inadvertently towards increased risk, for example by trialling new species or practices that may have an especially strong relationship with particular pests or pathogens. In terms of new technology, apps are being developed to promote increased awareness of risks amongst land managers and the public, and information campaigns such as Check Clean Dry for risks from INNS have been successful in raising prominence of the issues.

Integrated Pest Management (IPM) is an approach to risk management employed in some parts of the sector to link and improve the effectiveness of chemical and biological controls by reducing dependency on chemicals (including negative side-effects for biodiversity, soil quality, water quality, human health etc.). Further work to develop and expand this approach in the context of climate change adaptation, including knowledge exchange across the sector, would be very likely to have further benefits, especially with concerns over pesticide side-effects and pesticide resistance. In addition, as use of IPM is effectively voluntary, it is not currently known what the level of uptake is, especially as IPM implementation needs to both recognise market pressures and be cost-effective as well as being supported by good quality evidence and timely expert advice at local and regional scales to ensure effective uptake.

Another important type of initiative that can help build adaptive capacity is through recommendations on plant varieties and breeding, which can include trials on new pest/pathogen resistant varieties and national listing. At present the relationship with changing climate risks is included in advice from organisations such as AHDB and RHS but there is good scope for further development of such initiatives.

Moreover, in the context of the increased emphasis on delivering the Net Zero agenda, there is scope for further development of Integrated Pest Management (IPM) and plant trials/listing to enhance climate resilience and improve productivity and other goals in order to meet the Net Zero target.

### 3.8.2.3 Barriers preventing adaptation (N7)

Despite recent developments in concepts such as sustainable intensification, current agricultural systems tend to place their emphasis for production on intensive monoculture practices. In addition, globalized markets are driving the emergence and spread of new pathogens and INNS, and there is often an over-reliance on chemical applications to control the risk. Related to this are the increase in problematic traits, notably pesticide resistance, which may further exacerbate long-term risks, as exemplified by insecticide resistance (IRAG, 2018). Similarly new strains of fungi are emerging such as triazole-resistant *Z. tritici* in UK wheat, and new pathogens capable of overcoming inbred R genes, as with yellow rust in wheat (Fones *et al.*, 2020). At the landscape scale, loss of key features, such as field margins that can provide natural competitors and disrupt pathogen dispersion is also an underlying problem that has led to increased reliance on chemical solutions neglecting the principle that the most valuable weapon against pests and pathogens are typically a plant's own immune system and natural competitors of the problem species or micro-organism (Rusch *et al.*, 2016; Miller *et al.*, 2017).

Adaptation requires up-to-date information on the threat of establishment or spread to further encourage active surveillance, and complacency may be a concern in areas not previously exposed. It also requires co-operation beyond national boundaries, and this co-operation may be variable. Investigation of disease suppression has shown the importance of early detection and movement controls. For example, FMD controls in place since 2001 limited the bluetongue outbreak that later occurred in 2007, hence, further investment in new research that shows how control measures may be further optimised is likely to be beneficial (e.g., bluetongue restriction zones: Spooner *et al.*, 2020).

For INNS, identifying the actual pathways for invasion can be very difficult, even when assessed post-invasion (Roy *et al.*, 2014a). A review by Essl *et al.* (2015) indicated that throughout Europe, many invasion pathways remain unknown and that INNS can arrive through more than one pathway. Surveillance and control actions typically occur on a sectoral (or even sub-sectoral basis for specialist sectors such as horticulture) therefore actions are not always co-ordinated, and knowledge of changing risks can be variable. The risk may also be exacerbated because in some cases, management of INNS have fallen between multiple responsibilities (see oak processionary moth: Risk N8). Priorities to maintain or increase production can also mean that excessive risks (e.g., regarding material of unknown provenance) can be taken. It has also been suggested by some stakeholders commenting on the CCRA that there may be pressures from some businesses in the agricultural sector to relax regulations in order to enhance trade post-EU-exit or to improve productivity via new species.

These challenges are especially pronounced for emergent risks for which there may be very little information available and for which procedures for international and national (institutional and stakeholder) responses have not been agreed, and this may cause delays in enacting the necessary actions.

### 3.8.2.4 Adaptation shortfall (N7)

Institutional risk assessment procedures for pests, pathogens and INNS in agriculture currently provide some adaptive capacity. This helps to reduce the risk to a lower level at present and this will also have benefits in reducing risk in the future. However, we expect risks to continue to increase in future, including potential for emergent risks, which is therefore likely to present an increased challenge for existing procedures and indicates that there is scope for additional adaptation measures to lower residual risks to an acceptable level. The UK-wide and nation-specific strategies in place at the moment as set out above, do not include consideration of future climate risks including the potential impacts of up to a 4°C rise in global temperature. Confidence for the future is low due to the limited evidence on adaptation and the combined effects of climate and socioeconomic factors for this risk.

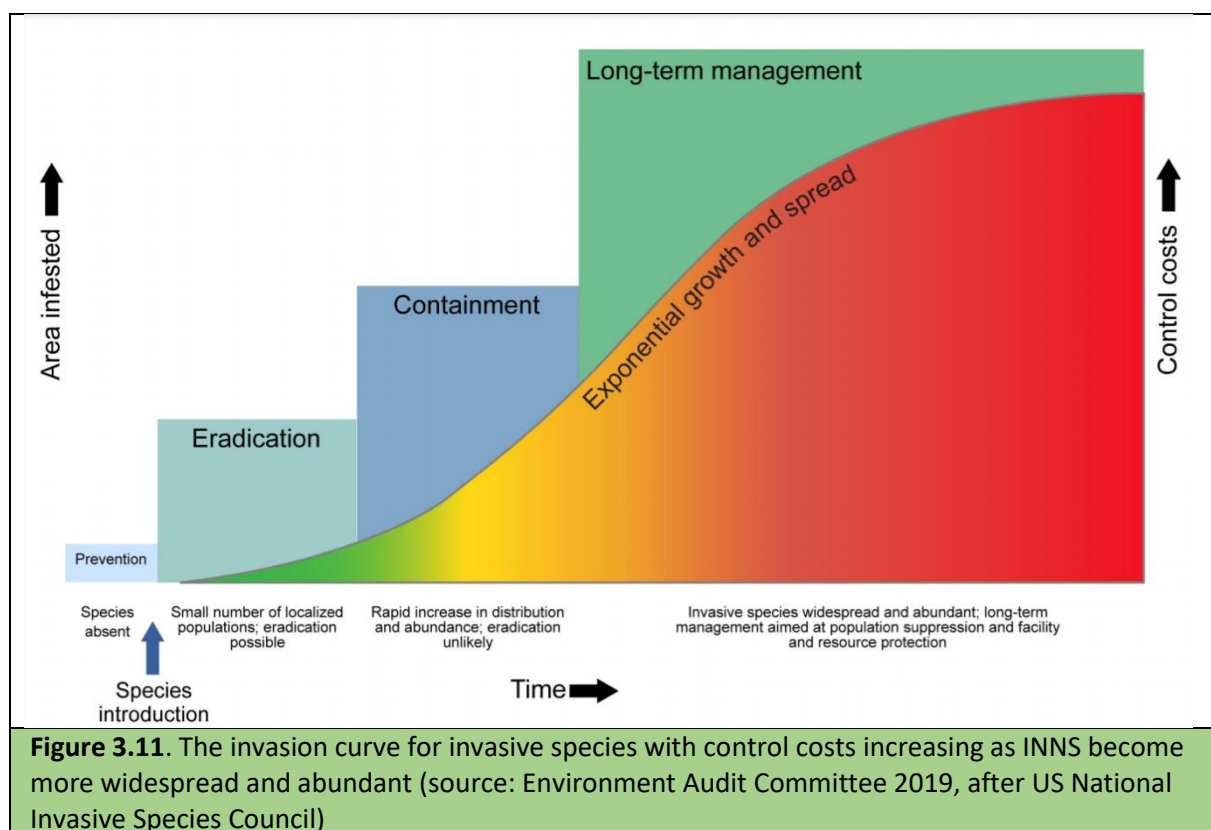
### 3.8.2.5 Adaptation Scores (N7)

<b>Table 3.24</b> Adaptation scores for risks to agriculture from pests, pathogens, and INNS			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

### 3.8.3 Benefits of further adaptation action in the next five years (N7)

For INNS, as shown by Figure 3.11 it is much more effective to prevent introduction and establishment rather than attempt to mitigate spread and resulting impacts. The same principles apply for averting introduction of problem pathogens.

Further assessment of climate factors in risk assessment would be beneficial in developing early warning systems. Quantitative analysis of climate change on crop pathogens remains limited (field, laboratory, or modelling studies). A more systematic programme of quantitative analysis is therefore required to inform development of disease management plans, such as plant breeding, altered planting schedules, chemical and biological control methods, and increased monitoring for new disease threats. Improved monitoring of pest and disease levels in UK crops and livestock could be used to provide more updated agronomic advice to growers, including best practice guidance on pest/pathogen biosecurity and management strategies. In addition, identification of plant and animal strains or breeds having greater natural resistance may be used in breeding programmes, including new assessments based upon genetic sequencing (e.g., late potato blight: Chen *et al.*, 2018). Enhanced use of modelling studies is also likely to be advantageous in surveillance and control strategies. For example, for PCN risk (Section 3.8.1), Skelsey *et al.*, (2018) found that soil infestation levels would have to be reduced by up to 40% in order to negate projected increases in risk. The same study identified that successful strategies to reduce future PCN risk were found to include advancing the start date of the growing season or modifying planting patterns.



Policy development following EU-Exit also creates an opportunity to further expand the uptake of IPM rather than rely on current voluntary uptake schemes, and to ensure that regulations adopt the principle of non-regression to ensure appropriate safeguards as risk factors change (e.g., international trade agreements). Increased support by government for IPM, including through a proposed National Action Plan, is very likely to be particularly useful in acting against excessive pesticide usage and its harmful side-effects for soil quality, water quality, and through pesticide resistance.

Further tightening plant health legislation in anticipation of increased risks is also likely to be required. The costs of tightening legislation could be i) a reduction in trade due to increased costs and ii) potential restrictions placed on exports from the UK by countries affected by the tightening of plant health legislation.

Evidence from this CCRA and in previous CCRA's suggests a greater priority be given to including climate change within risk assessments, and for this to be validated against changing distribution data for Europe and beyond, and where possible to be used to further investigate the efficacy of different control options. Following the Environment Audit Committee 2019 report, it is also suggested that a greater priority now be given also to a wider public engagement through citizen science initiatives to enhance surveillance. A positive example of this in practice has occurred through networks of bee-keepers to monitor Asian hornet risk (BeeBase, 2021).

### 3.8.3.1 Indicative costs and benefits of additional adaptation (N7)

Consistent with the discussion above, the economic case for further uptake of existing adaptation measures is sound, as evidenced by case study analysis on pests and pathogens (Watkiss *et al.*, 2019): it is much more effective to prevent introduction and establishment rather than attempt to mitigate spread and resulting impacts. However, this additional uptake of measures has an associated resource cost. There is a clear role for public co-ordination of monitoring and surveillance. Previous analysis by SRUC (2013) has identified that investment in monitoring for pests has a high benefit-cost ratio of around 10:1. The Environmental Audit Committee (2019) identified that expenditure on GB biosecurity is ca. £220 million per year, but invasive species only receive 0.4% of that sum (£0.9m). There are also clear benefits from Government investing in information about pests and pathogens – their spread, likely impacts, and treatment methods – as this information flow would not otherwise occur. Whilst a large proportion of the costs (for pests and pathogens) may be borne by private land-owners, public support is likely to be needed where there are local concentrations of economic activity that are threatened by the rapid spread of one of these pathogens in an area (to reduce the much larger costs once pests and pathogens become established). This economic argument is strengthened by climate change risks because the future nature of threats will in many cases be distant from private actors' past experience.

### 3.8.3.2 Overall urgency scores (N7)

<b>Table 3.25 Urgency scores for risks to agriculture from pests, pathogens, and INNS</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Medium	Medium	Medium

Because of the high projected magnitude for this risk, and the view that additional intervention is required to in the future to manage risk to low levels, in particular to integrate future climate scenarios into existing policies designed to control pests, pathogens and INNS, a 'More Action Needed' score has been assigned across the UK.

As well as enhancements of existing policies to take into account the changing risk due to climate change, improved surveillance and monitoring is required, especially in the context of the need for improved international co-ordination following EU-exit and associated trade agreements; this will require sustainable funding as it relies on a co-ordinated network of station data and part-private initiatives (AHDB pest bulletins; SRUC Crop Clinic in Scotland etc.). This also requires:

- Further development of international monitoring initiatives, surveillance, risk assessment procedures and bio-security measures based upon UKCP18 and other relevant climate change data.
- Enhanced horizon scanning for INNS from Europe and globally based upon changing international trade portfolio.
- Cross-sectoral initiatives for risk assessment and contingency planning using a range of diverse scenarios.

- Evaluation of risk reduction strategies for specific risks including prospects for resilient varieties and the use of increased diversification in plant and livestock species/varieties.

### 3.8.4 Looking ahead (N7)

- Improved risk assessments with space and time dimensions to evaluate changing dynamics of individual pests, pathogens and INNS, together with their changing status regarding prospects for future establishment and spread based upon both climate change and socioeconomic data (e.g., using combined scenario analysis, including land use change).
- Improved spatial profiling of risks including for extreme years to help better understand changing risk factors at a higher resolution across the UK.

## 3.9. Risks to forestry from pests, pathogens, and INNS (N8)

- Pests, pathogens and invasive non-native species present serious risks to forest productivity, with consequences for livelihoods and businesses, and for the multiple ecosystem services that forests provide.
- The combined effect of risk factors (climate and non-climate) indicates the magnitude of this risk is increasing. Across the limited set of known risks, we assess this risk as increasing from medium at present to high in the future.
- Existing risk assessment procedures provide some adaptive capacity which acts to reduce residual risk to lower levels at present. However, the scale of future climate change is very likely to mean new threats emerge that challenge existing measures, especially for pathways of higher magnitude of climate change.
- There is a need for further urgent action to improve preparedness, including enhanced surveillance and horizon scanning, and to address the increased prospect of emergent risks.

### Introduction

Pests, pathogens and invasive non-native species (INNS; see Glossary for definitions) present serious risks to forest productivity, with consequences for livelihoods and businesses, and for the multiple ecosystem services that forests provide. These individual risks have been combined together because climate change tends to blur their specific distinctions (e.g., some INNS are vectors for pathogens), and adaptation requires an integrated approach to biosecurity and surveillance.

The relationship of this risk with climate change is complex. Each problem species or micro-organism has its own specific climate sensitivities that can favour their increased incidence. This includes parameters related to maximum and minimum temperature, moisture (both precipitation and specific/relative humidity can have an influence), and potentially wind (notably direction); these typically act in combination and are also related to duration or frequency. In addition, socioeconomic factors are highly influential, both management factors at forest/stand level and large-scale drivers such as trends towards globalisation of trade and travel.



The combined risk factors (climate and non-climate) clearly suggest that the magnitude of this risk is increasing, despite uncertainty in attributing the relative influence of individual risk factors. In aggregate, across the range of known risks (only a limited set of which have been currently quantified), we assess this risk as increasing from medium (present) to high (future) based upon expert opinion, with the risk magnitude also being proportional to the degree of climate change. We also recognise limits on our knowledge of this climate risk relationship, more notably because the most severe outbreaks are typically related to extreme or anomalous climate conditions.

The current institutional risk assessment procedures provide some adaptive capacity that acts to reduce the residual risk to a lower level at present and this will also have continuing benefits in reducing residual risks in the future. However, future climate change, especially in a world with a higher magnitude of climate change, will almost certainly bring new risks that challenge current procedures, hence, there is a future adaptation deficit. There is therefore scope for additional urgent action to improve preparedness, including enhanced surveillance and horizon scanning, and to address the increased prospect of emergent risks (especially from novel pathogens) through additional contingency planning. The timing of emergent risks is especially uncertain meaning contingency planning can have benefits even for the present-day.

It is very likely that EU-exit will have important implications for this risk through modified trade arrangements and associated adjustments to regulatory regimes, but details on these changes remains very limited at present. In addition, we have very limited information on how COVID-19 may modify this risk beyond a general increased public awareness of the severe consequences that arise from spread of pathogens.

### 3.9.1 Current and future level of risk (N8)

#### 3.9.1.1 Current risk (N8)

In general terms, there is increasing evidence available that the rate at which new tree pests and pathogens are being introduced is increasing, primarily linked to the expansion of trade of timber and wood products, but with climate as an additional risk factor (e.g., Freer-Smith and Webber, 2015; Potter and Urquhart, 2017). Although challenges remain in attributing individual risk factors, we are confident in highlighting the risk of significant damage to forests in the UK which also extends to loss of the multiple ecosystem services that forests provide. This is supported by evidence from several sources, notably Defra pest risk assessments, incidence reporting on disease outbreaks in forestry (co-ordinated by Forest Research), and reports from the GB Non-native Species Secretariat and equivalent forum for Ireland. Nevertheless, forest pests and pathogens typically feature non-linear population dynamics and related feedback effects that currently confound a more complete understanding of changes in risk.

Several high priority pests in the UK Plant Risk Register have been identified with a climate link and strong relevance for forestry interests (risks for woodland biodiversity are assessed in Risk N2). For example, climate has been identified as a risk factor with regard to species such as emerald ash borer *Agrilus planipennis*. Previous CCRA's have highlighted climate-related risks in recent years from *Phytophthora ramorum* and *Dothistroma* needle blight, both of which have implications for conifer

production. *P. ramorum* is a fungal-line pathogen which has continued to spread in the UK, particularly in bioclimatic zones with high year-round moisture levels such as SW England, parts of Wales, Cumbria, SW Scotland and Argyll; however, rates of new larch infection have declined recently except in Wales, which may also be related to local climate variations. Similarly, *Dothistroma* needle blight has continued to spread north into Scotland, and in particular to affect east and north Scotland which have extensive areas of sensitive woodland. This pattern of infection has been linked with increasing precipitation in recent years during spring and summer together with warmer temperatures (Woods *et al.*, 2016). Damage is particularly severe for Corsican pine, but other affected species include lodgepole pine and Scots pine, the latter of which also has considerable amenity and biodiversity value (Brown and Webber, 2008).

Pest status for some species is associated with the damage caused by greater population numbers beyond a sustainable level. This is especially notable for native deer species that have benefited from increased frequency of warmer winters and which in a forest setting can cause considerable damage by browsing young trees. Deer are also very mobile and can range over a large area, as has occurred with the expansion of the red deer population in the Scottish Highlands where deer can move from sporting estates to forestry plantations whilst also preventing natural regeneration, although more evidence is required on these behaviours in the context of climate patterns.

Some syndromes associated with pests and pathogens appear to be due to the interaction of multiple stresses. For example, Acute Oak Decline, which is affecting native oaks in the UK, is principally caused by multiple, interacting bacterial species that degrade inner bark tissues, but the two spotted oak buprestid *Agilus biguttatus* which is an oak borer beetle, is also found to be strongly associated. A recent study has shown how historical episodes of stress, dating back as far as the 1930s may also be important factors and that correlations with climatic variables indicate that diseased trees are less able to take advantage of good growing conditions in the spring and autumn (Reed *et al.*, 2020).

As with agriculture (Risk N7), we have assumed that the primary direct climate change risk for INNS is associated with natural dispersion from continental Europe and therefore that it will affect southern UK areas first, whereas INNS that are introduced directly into the UK by human agency at any location may then indirectly benefit from climate change favouring establishment and subsequent spread. The impact on forestry from INNS is shown by species that have previously become established and have now spread, often aided by the shift to milder winters in recent decades. Pettorelli *et al.* (2019) identified impacts from climate change related movements of animals into new environments in GB since 2008, highlighting several with a woodland impact, including northward expansion of *A. biguttatus* to become established in the Manchester area, and box tree moth (*Cydalima perspectalis*) which has become established in the London area. Another example of a damaging animal INNS is the presence of muntjac deer and sika deer which have both increased in numbers in recent years, aided by the increased frequency of milder winters, to the detriment of the trees in forest plantations on which they browse (Armstrong *et al.*, 2020).

For softwood forestry production, bark beetles present an increased threat through damage caused to tree health and timber quality, notably the great spruce bark beetle (Forest Research, 2021a) which preys on spruce and pine and has become established in Wales, western England and

southern Scotland (not reported currently in Northern Ireland). In addition, the larger eight-toothed European spruce bark beetle (*Ips typographus*) has been recently detected in England (Forest Research, 2021b).

The changing patterns of risk for pests, pathogen and INNS, are strongly influenced by other socioeconomic factors that can facilitate their introduction to the UK and spread to new areas, notably through changing patterns of trade (and particularly through trade related to nurseries). In July 2019, 60 sites across UK were exposed to oak processionary moth (*Thaumetopoea processionea*) caterpillars due to the import of oak trees from the Netherlands and Germany. Warming and escape from natural co-evolved predators has allowed this moth species to expand its range in northern Europe from its original locations in southern and central Europe (de Boer and Harvey, 2020). It is now established in the Greater London areas and is primarily a risk for hardwood species and the multifunctional aspects of forestry management, rather than softwood production, and the caterpillars are a human health hazard (see Chapter 5: Kovats and Brisley, 2021).

In addition, new policy incentives may be further modifying risks. Expansion of trade in wood chips, as supported by policy proposals to increase bioenergy supply as a form of renewable energy, can act to increase the risk of imported material that contains infestations of damaging insect pests, including emerald ash borer beetle, bark beetle, and other *Agrilus* species. Although import regulations into Europe (usually from North America) are quite strict for coniferous wood chips (to control spread of pinewood nematode), they remain more relaxed for deciduous wood chips. This risk is averted by use of wood pellets, as utilised in the UK Drax power stations to meet its bioenergy quota requirement.

### 3.9.1.2 Future risk (N8)

Although knowledge has generally improved since CCRA2, investigations of climate change risk are still predominantly based upon a few pests, pathogens, or INNS, as ‘known knowns’. Therefore, although our knowledge of the underlying processes implies an increased risk from climate change, especially for higher magnitudes of change, confidence in the details remains low. The trend towards warmer and seasonally wetter conditions, especially in winter months, is very likely to favour increased risk from some existing pests and pathogens. However, as with agriculture, higher temperatures also present an additional risk factor through increased pathogen genetic variation and virulence, and hence for emerging pathogens (i.e., a new pathogen or a previously known pathogen in a new place or host), and together with the increased risk of introduction of novel INNS, these emergent risks represent both ‘known unknowns’ and even ‘unknown unknowns’.

Climate will act in combination with socio-economic drivers to determine the magnitude of risk, notably through globalisation and trade patterns. At local level, stand management, including trends towards either monocultures or diversification, will also be highly influential, especially in influencing the landscape-scale dynamics and dispersion of pests, pathogens and INNS through host species connectivity. In addition, changing choice and provenance of tree species (e.g., cherry), use of larger trees, and potentially greater demands for forestry products such as woodchip etc., will also have an important influence on risk management.

Existing evidence is based upon the known risks for individual pests and pathogens. Notable examples include *Ips typographus* (larger eight-toothed European spruce bark beetle), which, in addition to being intercepted in imports, has recently been recorded in England. This species could have severe consequences for the large spruce population in the UK and now has a Plant Health Order providing the basis for obligatory demarcation of outbreaks and associated movement restrictions on forest products. In addition, *Dendroctonus micans* (great spruce bark beetle) and *Elatobium abietinum* (green spruce aphid) both also present an increased risk. For example, risk of more frequent green spruce aphid attacks has been identified as a threat to Sitka spruce growth in west, east and south Wales (Berry *et al.*, 2019). It also seems likely that the increased drought stress expected in many areas of the UK in the future, as indicated by the trend to warmer drier summers in UKCP18, may make trees more vulnerable to pests and pathogen, although again we have limited evidence on these combined risk factors.

The use of exotic species in UK forestry has also been suggested to be an additional risk factor for pathogens (in addition to the risk from such species themselves for native biodiversity – Risk N2). This this can lead to emerging forest disease risk both by facilitating introduction of exotic pathogens and by providing susceptible hosts on which epidemics of native pathogens can develop, as shown by transfer of *Dothistroma septosporum* from non-native species to the Caledonian pine populations of Scotland (Piotrowska *et al.*, 2018; Ennos *et al.*, 2019). It is also likely that some patterns and types of land use patterns, such as large-scale monocultures, may facilitate the spread of some pests or pathogen vectors due to a lack of competitors. It is also possible that initiatives to enhance woodland connectivity by developing contiguous plantations may inadvertently enable spread of some pests and pathogens, unless appropriate counter measures (e.g., stand-scale management planning and diversification) are also implemented. Hence, measures that seek to enhance diversification in silviculture may be a key risk reduction strategy (Ray *et al.*, 2019; see also risk N6). In this context, diversification may conceivably include exotic non-native species as an option based upon a full balanced risk assessment; this may also require changing recognition of native/non-native distinctions in tree species across the different nations of the UK.

Climate change may also have indirect effects through interactions with pathogens. For example, spatial analysis of ash dieback disease caused by the fungus *Hymenoscyphus fraxineus* (commonly called *Chalara fraxinea*) using multiple GCMs and emission scenarios shows how climate change, by affecting host and pathogen separately, may uncouple their distribution and potentially in this case lower disease transmission in some regions of Europe, including the UK (Goberville *et al.*, 2016). Hence, ash may remain a viable future species in woodland ecosystems despite current concerns.

Confidence is low for projecting future risks from INNS because of the complex species-related interactions between climate change and changing socioeconomic drivers (see also Risk N2 and Risk N7). As the life cycles of many INNS are especially sensitive to warming, climate suitability will expand across the UK for an increasing number of problem species. Large-scale climate modelling of the distribution of invasive species shows that there is often a lack of clear consensus on the pattern of dispersion. Although analyses are most common for plants and invertebrates, meta-analysis suggests that larger shifts may be associated with invertebrates and pathogens whereas plants and vertebrates may be more generally associated with reduced range sizes (Bellard *et al.*, 2018).

The consensus view, based upon population increases in recent decades, is that further trends towards warmer winters are likely to increase the prospect of increased damage from deer to forestry production and other services (included carbon storage – see Risk N5), although impacts will also be influenced by local landscape structure (Spake *et al.*, 2020). Impacts will also be more severe in a scenario where deer numbers are not controlled at a sustainable level. This increased risk of deer damage includes both risks from native species and further problems related to the spread of INNS that are already established in the UK, notably muntjac and sika deer.

#### 3.9.1.3 Lock-in (N8)

As forestry decisions are long-term due to the time taken for trees to reach maturity, there is a higher potential risk from lock-in due to poor awareness of long-term consequences at the time of planting. Nevertheless, there is an increased awareness of the long-term issues in the forestry sector, as compared to agriculture, partly due to the legacy of past decisions such as large monocultures of certain species (notably Sitka spruce). This is primarily based upon production criteria, and the resultant implications for wider ecosystems services such as water quality, biodiversity and amenity value. This may mean that there are still contradictions regarding definitions of ‘long-term’ in forward planning: for some commercial plantations this can mean ca.35 years, whereas for some natural woodlands, especially where supported primarily by large old trees, it might be in excess of 100 years. This variation in the level of lock-in risk needs to be accounted for in risk management actions. The challenge for the sector will be therefore both to improve risk assessments to include the changing nature of currently-known risks but also to build in extra contingency to counteract expected emergent risks that are still unknown at present, also recognising that new INNS or pathogen introductions may have different impacts than in their native region.

#### 3.9.1.4 Thresholds (N8)

As discussed in more detail in Risk N2 and Risk N7, there are important climate thresholds (e.g., minimum temperature) related to both the establishment and spread of pests, pathogens and INNS, although these are specific to individual species or pathogens. Threshold-type models using key bioclimate metrics have been employed to assess the changing risks from some species or pathogens, as for example in risk assessments for *P. ramorum*.

#### 3.9.1.5 Cross-cutting risks and inter-dependencies (N8)

In addition to the obvious negative implications for forest productivity from large scale outbreaks, there are also in some cases important cross-sectoral interactions with agriculture, biodiversity, human health (Chapter 5: Kovats and Brisley, 2021), and landscape character (e.g., through loss of visual amenity or aesthetic qualities) including through loss of ecosystem services (Freer-Smith *et al.*, 2015; Boyd *et al.*, 2013). In addition, reduced biomass production from this risk may also have implications for carbon storage/sequestration targets (Risk N5). Pest and disease outbreaks can also reduce the resilience of forests and woodlands to wildfire by increasing fuel loading associated with both standing trees and surface litter. There is also the potential for secondary impacts on water and

soil quality if increased pesticide use, or new pesticide types, are employed to address the changing risk.

#### 3.9.1.6 Implications of Net Zero (N8)

The CCC Net Zero (2020) scenarios place a strong emphasis on woodland expansion combined with improved productivity. As identified above large-scale outbreaks may have implications for LULUCF targets defined for Net Zero by acting against productivity gains. In addition, although the central ('Balanced') CCC Net Zero (2020) scenario emphasises best management practice to avoid negative side-effects whilst enhancing productivity, as noted above there are wide variations in management practices currently in UK forestry as typically related to land owner/manager motivations for woodland creation (see also Risk N6). Hence, an over-emphasis on productivity without due regard for the need for associated good management practice, such as may occur with single-species monocultures, may act to increase negative impacts when outbreaks do occur. Further work is therefore required to assess the viability of the predicated productivity gains outlined in the Net Zero pathway in the context of an increased climate-related risk from pests, pathogens and INNS, including the implications from additional deployment of risk mitigation measures, notably biosecurity and diversification to enhance resilience, and the need to avoid other negative side-effects (e.g., for biodiversity, soil quality, and water quality).

#### 3.9.1.7 Inequalities (N8)

No evidence regarding inequalities associated with climate change were identified in relation to this risk. See Risk N2 for inequalities related to risks from pest, pathogens and INNS.

#### 3.9.1.8 Magnitude scores (N8)

Magnitude categories (Table 3.26) are based on expert judgement of existing/expected climate impacts on production and other forestry services (guided by existing risk assessments when available) due to the limited availability of quantitative data for this topic. Based upon climate sensitivity of known threats we expect this risk to substantially increase with future climate change, and to reach a high magnitude score under all but the lowest future climate change projections. However, confidence is low for future risks due to the interaction with socioeconomic factors and possibility of emergent risks.

**Table 3.26** Magnitude scores for risks to forestry from pests, pathogens, and INNS

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Medium	Med-High	High	High	High
	(High confidence)	(low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Northern Ireland	Medium	Med-High	High	High	High
	(High confidence)	(low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Scotland	Medium	Med-High	High	High	High
	(High confidence)	(low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Wales	Medium	Med-High	High	High	High
	(High confidence)	(low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

### 3.9.2 Extent to which current adaptation will manage the risk (N8)

#### 3.9.2.1 Effects of current adaptation policy and commitments on current and future risks (N8)

##### 3.9.2.1.1 UK-wide

The general policy context for this risk is the same as Risk N2 and referenced more fully in that section, including relationships to international agreements. Established risk assessment procedure for pests, pathogens, and INNS, covering both existing and new risks, include climate as a key factor. Adaptation policies for each UK country provide continued support for these procedures and biosecurity measures but cannot be regarded as fully robust because they do not define any additional measures based upon the changing risk from climate change, especially if the world were to follow a higher climate change trajectory, such as in a 4°C world. This is of particular concern for new emergent risks that may challenge existing protocols.

The UK Plant Health Risk Register records and rates risks to UK crops, trees, gardens, and ecosystems from plant pests and pathogens, including risk mitigation and new actions to manage or reduce risk. Forest Research maintains a comprehensive and regularly updated compendium of known risks from pests and pathogens to UK forestry, which also includes some information on climate suitability.

Recent enactment of EU Plant Health Regulations into national domestic law in each of the UK administrations has imposed tighter controls on the import and movement of plants and plant materials. However, Post EU-Exit trade agreements are uncertain and could increase the risks of pest/pathogen spread if the controls are relaxed.

The UK has agreed to meet international commitments to control INNS through the Bern Convention and CBD. The Aichi Targets, which fall under the CBD, included a commitment that by 2020 INNS and their pathways would be identified and prioritised, with priority species controlled or eradicated, and pathways managed to prevent species' introduction and establishment. However, in 2019 the UK Government has admitted that progress on meeting this target was "insufficient". As detailed for Risk N7, the GB Non-Native Species Secretariat (GBNNSS) coordinate assessment of INNS across England, Wales and Scotland, whilst Northern Ireland works on a whole-island basis with the Republic of Ireland in an All-Ireland Forum. Risk assessments are a key component of strategic planning and regulation, and if necessary, for legislation to reduce the risk of entry. The Invasive Alien Species (Enforcement and Permitting) Order 2019 introduces enforcement provisions, offences and penalties needed to comply with the requirements of the EU Invasive Alien Species Regulation and gives agencies, police and border force officials new powers to address Invasive Alien Species issues in England and Wales at an early stage. Similar legislation is planned for Scotland.

As identified in previous CCRAs and by the CCC, the current definition of INNS is based upon transfer beyond their native regions by human agency rather than when migration is assisted by a changing climate. This discrepancy is likely to have increasing ramifications for definition of, and actions against, INNS as they become increasingly assisted in their movements by a changing climate.

#### 3.9.2.1.2 England

The forestry sector has developed well-planned actions linked to specific threats as represented by the Defra (2018c) Tree Health Resilience Strategy. The forestry sector's 'Action Plan for Climate Change Adaptation of forests, woods and trees in England' sets out how the sector will enhance protection against the threat of pests and diseases within the context of climate change for the following 5 years. However, at present the 25 Year Environment Plan (25YEP) and second National Adaptation Programme (NAP2) do not outline a measurable goal for managing and reducing the impact of existing plant and animal diseases including for forestry.

#### 3.9.2.1.3 Northern Ireland

The importance of enhanced biosecurity has also been recognised here, including the role of the Plant Health Risk Register (led by DAERA) but again emphasis remains on support for existing measures. Progress from the first Invasive Species strategy (2013) for Northern Ireland was assessed in 2017 and it was concluded that the majority of targets within the 30 key actions had been achieved and steady progress was being made towards non-time limited targets. In 2018 the Invasive Alien Species implementation plan was revised but again explicit reference to climate change risks is rather limited. A recent catalogue of 'Pests and Pathogens of Trees on the Island of



Ireland' now provides a good reference source. There are also plans for further integration of Northern Ireland into a UK Non-native Species Secretariat.

#### 3.9.2.1.4 Scotland

The SCCAP2 highlights the importance of increased biosecurity specifically for forestry pests and pathogens, which links with the scope of the Scotland's Forestry Strategy, although more detailed adaptation actions that go beyond existing initiatives remain to be developed. The SCCAP2 also notes a new potential indicator for the future to record absence of INNS as a complement to the current indicator on presence of INNS.

#### 3.9.2.1.5 Wales

In Wales, adaptation plans also provide ongoing support for existing measures to address INNS and other nuisance species, including improved awareness through the Invasive Non-Native Species (INNS) Portal. Enhanced woodland diversification, as a measure to enhance resilience against increased future threats, is also supported by 'Woodland for Wales' (2018) – the national strategy for woodlands and trees. NRW's Area Statements give opportunities to address INNS in forestry and woodland and the 2nd Wales State of Natural Resources Report has identified four areas of focus for actions by helping to 'improve resilience, including to future climate change and pests and diseases'.

#### 3.9.2.2 Effects of non-Government adaptation (N8)

For the larger forestry stakeholders, much of the focus at present is on disease resistance (e.g., through genetic variation) and stand management to facilitate effective control if an outbreak is detected.

Land managers and others in the supply chain have an obligation to report incidences of specific threats and therefore are a key component of the surveillance system. However, pressures to improve production or trade through nurseries may sometimes lead inadvertently towards increased risk, for example by trialling new species or practices that may be especially associated with particular pests or pathogens (Potter and Urquhart, 2017).

An example of the challenges inherent in managing risks from a complex and dynamic pathogen is provided by the spread of *P. ramorum* which involved a large and diverse range of institutional, industry and private stakeholders (including forestry, horticultural and private garden interests), meaning it was challenging to formulate a coherent response (Potter and Urquhart, 2017). In this case, the complexity of the disease and the diverse range of interests cut across conventional administrative divides between plant health (Defra/Fera) and tree health (FC) responsibilities. However, the lessons learned were then employed to good effect in terms of developing a more proactive and joined-up response to the risk from ash dieback in more recent years. A key part of this response is a recognition of the need for more partnership working; stakeholders commenting on the CCRA have noted that the GB and Northern Ireland Tree Health Advisory Group should have an important co-ordinating role in this context but this has not met in recent years, further

emphasising the need to encourage more partnerships approaches. In addition, co-ordinated activities (e.g., official listing) to recognise more resistant varieties are underway which can further enhance adaptive capacity.

Information campaigns such as Keep It Clean (or Check, Clean and Dry in a more aquatic context – see Risk N12) have been successful at increasing broad awareness of the threats and the need to adopt good practice. In terms of stakeholder awareness, the British Woodland Survey in 2020 (BWS2020: Hemery *et al.*, 2020) showed there was strong awareness of environmental changes observed in woodlands in the last five years and that perceptions were that this risk was increasing, particularly for *Pathogen damage* (79% observing increase since 2015) and *Vertebrate pest damage* (55% observing increase since 2015). Pests and pathogens were considered the main factors influencing a change in management, with 66% of woodland owners in the 2020 survey considering diversifying tree species as a response. However, it should also be noted that forest surveys have shown that a significant proportion of the UK woodland stock is not ‘actively managed’ which may impede detection and control. BWS2020 found that most respondent woodland owners (69%) did not have a UKFS compliant management plan in place.

The Wales Invasive Non-Native Species Group includes many non-governmental organisations as members and has provided productive support towards tackling INNS in Wales. This includes work undertaken by local action groups and the Wales Resilient Ecological Network (WaREN).

### 3.9.2.3 Barriers preventing adaptation (N8)

As highlighted above for *P. ramorum*, new threats sometimes cut across conventional institutional responsibilities and require new ways of working and co-ordinated initiatives. Similarly, with the threat from oak processionary moth, it was originally not clear whether the primary responsibility was as a plant health issue or a public health issue, meaning there were delays whilst it was determined who should lead the response. In addition, adaptation requires up-to-date information on the threat of establishment or spread to further encourage active surveillance, and complacency may be a concern in areas not previously exposed. It also requires co-operation beyond national boundaries which may be variable. Investigation of disease suppression has shown the importance of early detection and movement controls.

Surveillance and control actions typically occur on a sectoral basis (or even a sub-sectoral basis for specialist sectors such as horticulture), so actions are not always co-ordinated, and knowledge of changing risks can be variable. Past incidents have shown that assumed priorities to maintain or increase production can mean that excessive risks (e.g., regarding material of unknown provenance) may be taken (Potter and Urquhart, 2017). It has also been suggested by some stakeholders commenting on the CCRA that there may be additional pressures to relax regulations in order to enhance trade following EU-exit, or to improve productivity via new species, which could also exacerbate risks, highlighting the need to better communicate costs and benefits of biosecurity measures throughout the sector including to the public (Eriksson *et al.*, 2019).

### 3.9.2.4 Adaptation shortfall (N8)

Existing institutional risk assessment procedures provide some adaptive capacity that will help to reduce the residual risk to a lower level than it would otherwise be given the increasing risks from climate change, and this will have continuing benefits in reducing residual risks in the future. However, future climate change, especially in a world with a higher magnitude of climate change, will almost certainly bring new risks that challenge current procedures. In particular, as with the other risks in this chapter considering pests, diseases and particularly for INNS, what is missing is explicit recognition of the changing risk from climate change in the policies mentioned above, including scenarios up to a 4°C world. Risk management strategies therefore require further extension to better recognise emergent risks rather than just the 'known knowns' and also to develop a stronger long-term adaptation perspective based upon multiple future scenarios. Hence the anticipated threat is only partially addressed and there is a future adaptation shortfall. Confidence is low because of the limited evidence on the efficacy of adaptation measures and because of the complex interaction of climate risks with socio-economic factors.

### 3.9.2.5 Adaptation Scores (N8)

<b>Table 3.27. Adaptation scores risks to forestry from pests, pathogens, and INNS</b>			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

### 3.9.3 Benefits of further adaptation action in the next five years (N8)

As with risks N2 and N7, with which there are many commonalities, the need for cross-sectoral co-ordination and surveillance requires more action and research especially focussed on the following issues:

- Surveillance and modelling for emerging risks.
- Further modelling of risk reduction measures for pests, pathogens and INNS.
- Further assessment of climate factors in risk assessment that would be beneficial in early warning.
- Understanding current and future risk from non-native species vectors and pathogens.
- Improved biosecurity, especially at ports of entry.
- Changes to plant purchasing and sourcing practices to highlight importance of secure sources and provenance (e.g., certification).
- Increased emphasis on disease and pest resilience.
- Further investigation of management initiatives to enhance resilience, such as diversification (see adaptation options investigated for forestry in Risk N6).
- Improved understanding of current and future risk from non-native tree species used, or proposed, for enhanced production purposes.

The role of genetics may have an important role in developing improved resilience to pests and pathogens (Telford *et al.*, 2015; Fady *et al.*, 2016). This may include changes to the chosen provenance of tree planting stock (e.g., seed sourcing) based upon known resistant varieties and improved knowledge exchange with land managers on this topic, especially where the goals for forestry are multifunctional and not just related to production (Whittet *et al.*, 2019).

### 3.9.3.1 Indicative costs and benefits of additional adaptation (N8)

The economic case for further uptake of existing adaptation measures is sound, as evidenced by the discussion above: it is much more effective to prevent introduction and establishment rather than attempt to mitigate spread and resulting impacts. Watkiss *et al.* (2019) explored the possible costs and benefits of adaptation for a number of forest pests and pathogens (once established). The analysis indicated that it is possible to manage changing pathogen risks, at least to some extent, using existing adaptation options. However, there are large resource costs associated. There are therefore benefits from further adaptation that avoids these risks. This includes a key role for public co-ordination of monitoring and surveillance.

Previous analysis by SRUC (2013) has identified that investment in monitoring for pests has a high benefit-cost ratio of around 10:1. There are also clear benefits from Government investing in information about pests and pathogens – their spread, likely impacts, and treatment methods – as this information flow would not otherwise occur. Whilst a large proportion of the costs (for pests and pathogens) may be borne by private land-owners, public support is likely to be needed where there are local concentrations of economic activity that are threatened by the rapid spread of one of these pathogens in an area (to reduce the much larger costs once pests and pathogens become established, i.e., management plans and emergency response). This economic argument is strengthened by climate change, because the future nature of the threats will be less understood by private actors' past experience.

Cost-benefit analysis of enhanced measures to address INNS are also discussed in Risk N7.

### 3.9.3.2 Overall urgency scores (N8)

<b>Table 3.28 Urgency scores for risks to forestry from pests, pathogens, and INNS</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Quality of evidence</b>	Medium	Medium	Medium	Medium

A 'More Action Needed' score based on medium quality of evidence has been assigned to this risk. The high projected magnitude for this risk in future (which would be very likely to become even more pronounced under higher scenarios of climate change) and the severe challenges presented to

existing procedures (increase in risk species and micro-organisms, including emergent threats) indicate the need for further measures to to reduce risk.

Improved surveillance is required, especially in the context of the need for improved international co-ordination following EU-exit and associated trade agreements. It is also suggested to continue current research efforts into the impact of climate change on long-term risks. Cross-sectoral initiatives for risk assessment and contingency planning should include the following:

- Further development of international monitoring initiatives, surveillance, risk assessment procedures and bio-security measures based upon UKCP18 and other relevant climate change data.
- Enhanced horizon scanning for INNS from Europe and based upon a changing international trade portfolio. Cross-sectoral initiatives for risk assessment and contingency planning using a range of diverse scenarios (including with agriculture, horticulture, and biodiversity sectors).

#### 3.9.4 Looking ahead (N8)

Improved spatial and temporal profiling of specific risks including for years with particularly extreme weather would help to better understand changing risk factors in combination with changing socioeconomic factors (e.g., trade patterns).

### 3.10. Opportunities for agricultural and forestry productivity from new/alternative species becoming suitable (N9)

- Future climate change, especially warming, will enhance climate suitability for new crops. However, there is limited evidence available to assess the magnitude of potential opportunities.
- In agriculture and horticulture, a wide range of potential opportunities may be identified, some of which are already being developed as niche crops in suitable areas.
- In forestry, trees that are cold-limited and presently restricted to lowland areas and southern England will be suitable for growing in increasing areas in a warming climate.
- Based on limited evidence, the assessment concludes the level of opportunity will increase from medium at present to potentially high in the future.
- Inertia in land use decision-making at multiple levels of society means much of the adaptation opportunity for agricultural and forestry productivity remains unrealised.
- This topic has been assessed as a priority for 'Further Investigation' in conjunction with ongoing policy initiatives to advance the innovation economy in the UK.
- Changes in trade and regulatory agreements following the UK's departure from the EU will have important implications for this topic.
- Realisation of opportunities will also require that associated risks to the agriculture and forestry sectors (N6, N7, N8) and to soil health (N4) are also effectively managed.

## Introduction

We have defined this opportunity-related topic in the broader sense to include climate-related developments that can occur through new species, varieties, and cultivars, together with any new cropping combinations (either as mono- or inter-crop combinations). It also includes the potential for movement of existing species (or varieties/cultivars) in one UK country or region into another country/region, thereby presenting novel opportunities in that new location. In each of these cases, agricultural or forest productivity may be enhanced. As previously discussed for Risk N6, sustainable productivity issues are a key challenge for the natural environment, and of high relevance not only to land managers and rural communities but also the population as a whole due to the implications for domestic supply of food and other commodities.

The level of opportunity is assessed to increase from medium (present) to possibly high in future, although evidence is rather limited. Much of this opportunity remains unrealised in terms of adaptation. This is probably due to inertia in decision-making at multiple levels of society from land managers to institutions and policy: for example, inertia is exemplified by a focus on climate change 'resilience' being interpreted as maintenance or enhancement of current production systems. Therefore, this topic is recommended as a priority for 'Further Investigation' in conjunction with ongoing policy initiatives to advance the innovation economy in the UK.

As with Risk N6, it is very likely that EU-exit will have important implications for this topic, but this will be very dependent on how it changes trade and regulatory agreements. COVID-19 may also have important implications but at present there is very little evidence on these wider interactions.

### 3.10.1 Current and future level of opportunity (N9)

#### 3.10.1.1 Current opportunity (N9)

There is presently limited information on the establishment and spread of new crops and other exotic produce, especially in a spatial context. Prominent examples that have featured in news item-type reports include chickpeas, quinoa, vines, soya, and lentils. Other crops known to have been grown recently in the UK include peaches, apricots, tea, sunflowers, sweet potatoes, watermelons and walnuts, whereas exotic produce has recently extended to include truffles (Thomas and Buntgen, 2018). However, some of these crops are grown in sample trials developed within the ethos of agricultural/horticultural entrepreneurship rather than being developments that have led to actual commercial-scale production opportunities. In some cases (e.g., apricots), new opportunities are associated with hardy new cultivars that appear to be more adapted to the variable UK climate, especially the continuing risk of occasional frosts.

The area under vines in the UK has increased by 160% in the past 10 years and is currently around 2500 ha. About 700 vineyards exist (of which about 75-80% are commercial), and over 160 wineries (WineGB, 2018). In 2018, 1.6 million vines were planted with a further 2 million planned for 2019 (but not confirmed). The variability of the UK climate involves challenges for production with inevitable 'good' and 'bad' years. The hot dry summer of 2018 meant that a record 15.6 million bottles of wine were produced (the previous record was 6.3 million bottles in 2014) (ADAS, 2019). Some other recent years have been poor for production, notably 2012 which featured a very wet

cloudy summer in the wine-growing areas. Analysis of current vineyard locations using a Viniculture Suitability model based upon bioclimate, soil, topography and other data has shown that they are rather sub-optimally located when compared to the most favourable sites from a biophysical perspective (Nesbitt *et al.*, 2018), emphasising again the underlying socioeconomic factors that influence land use decisions (see Risk N6). Nevertheless, in a warming climate, enhanced suitability for viniculture and wine production presents an important business opportunity to move away from traditional crops (see also Chapter 6: Surminski, 2021).

An expanding crop in the UK is soya, with the area increasing from 8 ha to 500 ha between 2012 and 2017, as warmer temperatures are providing a larger area of the UK suitable for production. Triticale (a wheat/rye hybrid) is another crop with significant opportunities that has actually been present in the UK for a long time, but with limited uptake (less than 0.2% of current cereal production). Most commonly, it has been a second arable rotation crop following wheat due to its better resistance to root take-all disease. Triticale is mainly used for forage, but can be used in cereal food products, bioethanol, and anaerobic digesters. Compared to wheat, yields of triticale seem quite robust both to cooler wetter summers (e.g., 2012) and to drought conditions, despite slightly higher lodging risk (Bassu *et al.*, 2011; Roques *et al.*, 2017). Triticale has a more developed rooting system than wheat which means it can be more effective in capturing soil nutrients, hence requiring less fertiliser, with reduced soil N losses to air and water (and P losses to water). The resulting reduced N<sub>2</sub>O emissions mean it has been identified as a good candidate for climate mitigation policies linked to Net Zero GHGs, with indicative emission reduction factors scoped by CCC (2020) but also further assessment required. The extensive roots have good soil binding potential, especially with lighter soils, which can reduce erosion risk, and it can also enhance organic matter and improve soil structure with good management practice. However, it is not yet fully known how the changing suitability for triticale cropping, and its relative advantages compared to wheat, will vary with future climate change projections, although existing information indicates it may be more resilient to extreme events.

Potential production opportunities already also exist through intercropping, both as whole crop silage and harvest for grain, although uptake is limited at present. Intercropping uses complementary plant relationships (species mixtures such as cereal/legume; or cultivar mixtures) to enhance productivity or reduce inputs, and there is increasing interest in using such approaches for climate adaptation with large-scale meta-analysis showing potential for greater yield stability from cereal-grain legume intercropping (Raseduzzaman and Jensen, 2017). At a field trial site in eastern Scotland, Newton *et al.* (2019) evaluated cultivar mixtures of winter barley and spring barley during 2015-16 compared to equivalent monocultures and found overall grain yields significantly higher for the cultivar mixtures and also that these mixtures decreased rhynchosporium disease for most non-fungicide treatments. Evidence was less conclusive regarding straw yield, which may be more sensitive to interannual climate variability.

Forestry has a more co-ordinated programme for trialling new species, including evaluation of the most suited provenances to allow trees to adapt to UK conditions. Forestry Commission (FC) data indicate that ca. 25% of trees planted in FC forests are currently less traditional species. This includes species that are fast growing and therefore provide opportunities for enhanced productivity but may also present additional risks, such as from wildfire (e.g., eucalyptus). Climate warming is also

allowing expansion in the use of some established productive species into new areas (e.g., Douglas fir).

An important driver for pioneering new crops and varieties is the Net Zero GHG agenda, through which production gains are associated with reduced GHG emissions, either through direct effects on emissions pathways or indirectly by sparing land for alternative land uses as carbon sinks (notably forestry). In addition to new cultivars such as crops bred for enhanced N-use efficiency crops, this may also include further expansion of existing crops such as triticale. Another noteworthy example, which may be especially relevant for the wetter areas of the UK where livestock farming dominates is the development of High Sugar Grasses (HSGs) that can provide more forage energy and therefore protein, which in turn can increase livestock meat and milk production, while reducing N losses to air and water (Parsons *et al.*, 2011; Soteriades *et al.*, 2018).

### 3.10.1.2 Future opportunity (N9)

Future climate change, especially warming, will enhance climate suitability for new crops but, by comparison with research on changing suitability for existing conventional crops, there is limited evidence currently available to assess the magnitude of potential opportunities. Notable exceptions include previous analysis of changing suitability for bioenergy crops in a warming climate in the UK which identifies opportunities for expansion of some crops into new areas (e.g., Bellarby *et al.*, 2010), and recently-derived suitability analysis of a wide range of crops in Wales based upon UKCP18 data and bioclimate metrics (Bell *et al.*, 2019). The latter included novel crops (e.g., tea and almond) in addition to existing crops and indicated potential for expansion in some cases. However, it should also be noted that some of these novel crops typically have a high water requirement to sustain growth and this reduces their suitability, including in existing areas. The suitability analysis in Wales identifies drought risk as a key constraint that increases in future and as discussed in Risk N6 this would be an even more significant factor in some areas of eastern England. Nevertheless, for crops that are adapted to limited water availability this may provide new opportunities. It should also be noted that existing work on changing crop suitability does not consider advances in crop genetics, under-cover cultivation, hydroponics, aeroponics or other technologies, or availability of supplemental irrigation. In addition, local variations in the capability of the land may also be crucial, as occurs with topography, aspect and microclimate (e.g., south-facing versus north-facing slopes) and different soil types (e.g., water-intensive bioenergy crops may be suited to alluvial soils on fluvial floodplains but less suited for more marginal soils, such as thinner soils on valley sides). Suitability analysis will also require to be further refined to include changes in productivity that occur due to elevated atmospheric CO<sub>2</sub> levels (and related feedback issues such as water requirements and water-use efficiency).

Analysis of opportunities from viticulture generally report positive outcomes in a future climate, although often do not consider the full suite of variables that may affect wine production. For example, in a scenario reaching approximately 3°C global warming at the end of the century<sup>20</sup>, large areas of the UK (excluding the wetter western regions) may be suitable for viticulture in 2100, mostly for white grape varieties and Pinot Noir, although not in this scenario for warm climate grape

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<sup>20</sup> Unspecified climate model driven by the RCP6.0 concentrations pathway



varieties such as Sangiovese, Cabernet Sauvignon and Grenache/Garnacha. (Georgeson and Maslin, 2017). The same indicative analysis also inferred to an increasing risk that current wine-producing areas in the south of England may become less suitable for some of the cool climate grape varieties, such as Pinot Noir, but may have the potential for intermediate climate red wine grapes (e.g., Merlot and Tempranillo) in favourable locations such as Kent, Essex, Norfolk and Cambridgeshire. Climate change could therefore open a range of opportunities for growing different varieties of grapes, depending on future magnitudes of warming but also changing seasonal rainfall patterns (heavy autumn rainfall can be particularly detrimental). Viniculture is also affected by temperature variability and extremes, notably from the frequency and intensity of mid-winter low temperature, late spring frosts, and the influence of excessive summer heat (Nesbitt *et al.*, 2016). An analysis of the opportunities for wine in the UK was undertaken as part of the CCC outcomes project (Watkiss *et al.*, 2019), based on the literature and wine sector ambitions. This estimated that if a 10% increase in production was realised by the 2050s (based on long-term wine sector goals), this would translate to additional revenues of approximately £22-80 million/year. A higher estimate, based on a 25% increase, could lead to additional benefits in the range of £54-200 million/year. These figures are based upon multi-year averages, but high annual production variability is also noted, and an increase in interannual climate variability would be likely to have negative implications with significant contrasts between good and bad years, as occurs at present. An additional factor will be climate change impacts on wine growing areas in other countries, which if negative (as some studies suggest) could create increased export opportunities for the UK.

For forestry, trees that are cold-limited and presently restricted to lowland areas and southern England (both native and non-native species) will be suitable for growing in increasing areas in a warming climate (Forestry Commission, 2020b). This includes productive species, such as eucalyptus, radiata pine (although potentially vulnerable to *Dothistroma* needle blight), red fir, and silver fir, together with productive broadleaf species such as lime, false acacia, London plane, field maple, and aspen, and those species which are valued for other distinctive properties (e.g., in woodcraft; amenity value; fruits and nut production) such as sweet chestnut, hornbeam, cherry, and walnut, especially if natural regeneration is facilitated. Further opportunities for expansion of existing established species such as Douglas fir and sycamore are also very likely to occur and fast-growing species that are selected for bioenergy sources (e.g., black poplar) will also benefit from warming. Emphasis will also need to be placed on tree species selection matched to the right soil type and other conditions such as soil moisture, and exposure. Notably, the projected reduction in summer soil moisture for eastern England and increased frequency of drought conditions may exclude sensitive species from these locations. In addition, some species may become more vulnerable to pests and diseases (Risk N8). For some species (e.g., poplar), climate warming may also allow the use of clones that are currently not hardy in Britain.

Another land use option with potential new opportunities is agroforestry. Although agroforestry systems have existed in the UK for centuries, present use is very much diminished (see Risk N6). However, the changing climate offers scope for new combinations, either for trees with pasture or arable, and this is another future option that deserves further investigation, especially in the contexts of multiple benefits and not only for production objectives.

#### 3.10.1.3 Lock-in (N9)

Inertia in the agriculture and forestry sector may prevent the transition to more productive and efficient crops (efficiency here being defined as maximised outputs per unit of input whilst also reducing negative externalities). For some crops, lock-in could be a risk. Watkiss *et al.* (2019) highlighted that the expansion of cultivated area for wine (new planting) involves long lifetimes and considerable lock-in, because it requires land-use change and high capital investment. The payback period on wine is longer than for many other agricultural crops, and this means that early decisions on new expansion areas in the short- and medium-term need to be evaluated against the future climate in the medium-term and even in the longer-term.

#### 3.10.1.4 Thresholds (N9)

As identified by CCRA2 and discussed further for Risk N6, there are important bioclimate thresholds related to species requirements, especially temperature and moisture thresholds, which can be characterised through the changing patterns of UK land suitability for each species. The analysis of changing crop suitability in Wales referred to above (Bell *et al.*, 2019) has used this mode of analysis to define different levels of suitability based upon multiple bioclimate variables for each selected crop.

#### 3.10.1.5 Cross-cutting risks and inter-dependencies (N9)

There are known and unknown risks from pests, pathogens and INNS which may impact on productivity (Risks N7 and N8). Pests, pathogens, or INNS may present particularly damaging challenges for newly introduced crops or varieties, as their natural enemies/competitors may not be present in the UK; in addition, they may have detrimental impacts on pollinators, which are an essential requirement for the production of some crops (Vanbergen *et al.*, 2018). Newly introduced crops or trees may have a negative impact on biodiversity because they offer less support for native invertebrates; this may then affect other trophic levels that rely on invertebrates. In addition, for some crops there will be important interactions (positive and negative) with soil, air and water quality. More specifically, fast-growing crops (including tree species used for short-rotation coppice or short-rotation forestry) that may be prioritised for production purposes also tend to have high water requirements, and in some cases novel species (e.g., eucalyptus) can have a high fire risk as has been found from large-scale planting in other countries (Mirra *et al.*, 2017; Nolan *et al.*, 2018; Belcher *et al.*, 2021). The role of new crops within arable rotations may be especially important in delivering co-benefits in addition to production objectives. Evidence for most of these cross-cutting risks and their interaction with opportunities in agriculture and forestry due to climate change is very limited in the UK but potentially available from other countries, although the land-use context may be different.

#### 3.10.1.6 Implications for Net Zero (N9)

As noted above, there are important interactions with the Net Zero GHG agenda in terms of potentially reduced emissions, and some new crops may provide additional health and nutritional

benefits that enhances efficiency of food supply per unit of equivalent carbon emissions. Further work using life-cycle analysis would be beneficial to confirm these putative gains. Analysis of energy crops (SRC, miscanthus etc.) suggests there may be a useful co-benefit for potential flood alleviation if planting occurs to replace arable crops on floodplains due to their additional hydraulic effects in slowing river flow (Rose and Rosolova, 2015).

### 3.10.1.7 Inequalities (N9)

As discussed for Risk N6, availability of good quality, nutritious, food is also an important human health issue and in negative terms can be associated with issues of 'food poverty' that can especially affect more vulnerable people in society. Opportunities for new produce through novel species or varieties, can potentially have an important role in addressing these societal challenges, particularly when linked with local food initiatives that enhance the supply of fruit, vegetables, and other staple foods.

However, no specific evidence showing how inequalities may be modified through this climate change opportunity has presently been identified.

### 3.10.1.8 Magnitude scores (N9)

**Table 3.29** Magnitude scores for opportunities for agricultural and forestry productivity from new/alternative species becoming suitable.

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Medium	Medium-High	High	High	High
	(Low confidence)	(low confidence)	(low confidence)	(Low confidence)	(Low confidence)
Northern Ireland	Medium	Medium-High	High	High	High
	(Low confidence)	(low confidence)	(low confidence)	(Low confidence)	(Low confidence)
Scotland	Medium	Medium-High	High	High	High
	(Low confidence)	(low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Wales	Medium	Medium-High	High	High	High
	(Low confidence)	(low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

Notes: Magnitude categories are based on expert judgement of existing/expected impacts on production outputs due to the limited available quantitative data for this topic. As many crop types and tree species have a clear climate sensitivity which influences when and where they can be cultivated, we have projected that the potential opportunity increases from medium (present) to high under most future climate projections, although it may not increase by quite as much by 2050 on the lowest trajectory of future climate change. Confidence is low for all of this assessment due to the limited information available, especially when extrapolating to a national scale.

### 3.10.2 Extent to which current adaptation will manage the opportunity (N9)

#### 3.10.2.1 Effects of current adaptation policy and commitments on current and future risks (N9)

Existing national policy frameworks that have relevant commitments for adopting new species in agriculture and forestry production are discussed in Risk N6. As highlighted there, much of the emphasis across all UK nations is on 'climate resilience', interpreted in terms of enhanced production from current systems. Current policy support throughout the UK is therefore limited with regard to new opportunities for new species, although some is provided through associated funding for long-term crop trials and new evidence-support initiatives such as the changing crop suitability analysis for the Capability, Suitability and Climate Programme in Wales (Barrow et al, 2019, referred to above). These initiatives are providing an initial step in highlighting spatial variations in the availability of new opportunities. We have been unable to find specific examples of other government initiatives that focus on supporting the uptake of new species in agriculture or forestry in the context of climate change adaptation.

This topic therefore currently appears to be seen predominantly as an industry-led issue linked to market opportunities. With commitments for Net Zero GHG emissions and national Food & Drink strategies promoting a shift towards more local/national production and healthy diets, this lack of government support may be seen as an important adaptation gap if the market involves barriers to uptake. In response, initiatives that allow policy to become more of an enabler and to support entrepreneurship regarding new opportunities can be identified as a valuable mechanism to enhance adaptive capacity. For example, this may include the use of grants (analogous to support for new technology), support for specialist knowledge exchange networks, and an increased role for an innovation-related organisation to act as a champion and lead coordinator between research and industry.

While the private sector would be expected to take advantage of opportunities, there may be an important role for Government in order to fully realise these benefits. An example has been given for the wine industry (Watkiss *et al.*, 2019), which found there was a potential role for Government to provide the enabling environment to take advantage of the positive changes in suitability and productivity being seen in the UK. This includes the provision of information (including for future wine suitability) which is particularly important given the lock-in involved with the expansion of wine production areas (i.e., for wine investment decisions in the next decade due to the long-life time and high capital investment costs for vines).

### 3.10.2.2 Effects of non-Government adaptation (N9)

In agriculture, opportunities are being investigated by industry and individual farmers, but research is often limited compared to the scale of investment in conventional species/varieties. Typically, the level of investment in new crops or cropping systems is linked to perceptions of market opportunities and the level of risk incurred by that investment relative to future economic returns. Adoption and spatial diffusion of new crops, including the contingent interaction of supply and demand, typically takes rather longer than anticipated with time lags for the UK between early and full adoption of about 20 years based upon both empirical analysis and simulations (Alexander *et al.*, 2013). For example, investment in triticale is extremely small compared to the large-scale research programmes developed for wheat, although information is gradually being collated on its relative advantages and market opportunities, including a recent AHDB and Innovate UK funded project (Clark *et al.*, 2016). More generally, AHDB provide advice and guidance for some species and especially on new cultivars. However, to better anticipate and realise some of the new opportunities provided by climate change, more knowledge exchange, co-ordination of initiatives, and outreach activities such as demonstration projects to build adaptive capacity is required.

The forestry sector has a more established programme of trialling opportunities from new species. For example, the 'Silvifuture' network ([silvifuture.org.uk](http://silvifuture.org.uk)) has been established to promote and share knowledge about novel forest species across Britain.

A very interesting example of the development of local-scale opportunities is the introduction and cultivation of non-traditional crops by particular ethnic groups at community level, including as allotment-holders, and in some cases subsequently being grown on a commercial scale. A recent survey and inventory of exotic crops grown on allotments (e.g., white maize, callaloo, dudi (bottle gourd), okra, chayote, and honeyberry), including by whom and why they are grown, provides a very useful baseline (Kell *et al.*, 2018). The majority of smallholders save their own seed, indicating crops are performing well in the UK and that this diversity is being maintained over the longer term, whilst also swapping seed with other growers, which further enhances diversity in response to different growing conditions, including climate conditions well beyond their normal range. A study of European commercial plant nurseries showed that 73% of garden species were able to survive an average of 1000km further north than their known natural range limits usually through a modified microclimate (greenhouses, walled gardens, polytunnels, hotbeds etc.) (Van der Veken *et al.*, 2008).

### 3.10.2.3 Barriers preventing adaptation (N9)

There is presently limited information on new opportunities targeted at breeders and growers. For example, AHDB provide lists of recommended crops and cultivars and these could be expanded to include a measure of durability to climate. In addition, the breeding profile and trials could have an improved evaluation of climate information, including variability and extremes (Falloon *et al.*, 2018), to allow more informed decisions on the balance between risk/opportunity regarding crop/cultivar choice.

Another practical barrier is the refinements in processing technology (food, fibre or energy) that may be required to enable opportunities to be realised. For example, the harder texture and larger

grain size of triticale are currently associated with lower milling yield compared to wheat (Dennett and Trethowan, 2013). A large-scale shift to more efficient use of triticale in flour production would require refinements to current milling technology which are currently specified based upon the requirements for wheat. Similarly, there have been concerns that use of miscanthus in bioenergy production using a conventional sodium hydroxide or sulphuric acid pre-treatment can have negative side-effects due to acidification, soil toxicity, and eutrophication impacts from residues unless processing plant is further modified (or, potentially, hot water pre-treatment is used instead) (Lask *et al.*, 2019).

These concerns identify a deeper underlying issue which relate to the difficulties in new opportunities being realised when in competition with existing uses. For example, commercial development and planting of new crops/cultivars is often dependent on other locational issues such as the availability of processing plant and related demand from the food, drink or energy sector. This may require significant capital investment and the development of centralised resources to facilitate these synergies, but this is typically beyond a small-scale grower and requires either the involvement of larger businesses, increased business co-operation, or an increased role for policy in stimulating local or regional opportunities, these issues are further discussed in Chapter 6. Similarly, in the forestry sector, although an interest in growing more exotic species has been noted, the availability of markets for these species has acted as a significant barrier (Lawrence and Marzano, 2014). Stakeholder analysis in the Scottish forestry sector has also highlighted that species choice is a social as well as an economic and technical choice, because different people involved in land use have different objectives and preferences (Lawrence, 2020).

There is therefore a potential role for Government to support early actions to address existing information and other barriers and create an enabling environment for the private sector. However, for political reasons, some government departments are not keen to be openly promoting increased uptake of opportunities as this might be seen as welcoming climate change.

#### 3.10.2.4 Adaptation shortfall (N9)

Our interpretation of the limited evidence for this topic is that much of the adaptation opportunity for agricultural and forestry productivity remains unrealised due in large part to inertia in decision-making at multiple level of society. At present, the topic appears to be seen as predominantly an industry-led issue linked to market opportunities; however, there is likely to be an important role for Government in order to fully realise these benefits by providing support and information, and by removing other barriers to greater uptake (see below).

At present therefore, it is our assessment that most of this benefit will not be realised in the absence of additional government intervention. This should be a major source of concern because the opportunities identified here could provide the potential for increased domestic and local food supply, reducing the reliance on imported food. With future population projections showing a continued increase in the UK population over coming decades (around 10 million more people by 2050 under a central projection), even if the same balance between domestic and overseas food supply is assumed (e.g., as in the CCC (2020) Net Zero scenarios) then an increased domestic supply

will be required to meet increased demand. As highlighted also for Risk N6, at present it is not clear how this increased demand will be met in a changing climate, notwithstanding other potentially major socioeconomic changes, such as changes in diet or reduced food waste. Confidence in the assessment of current levels of adaptation is low because of the limited evidence.

### 3.10.2.5 Adaptation Scores (N9)

<b>Table 3.30 Opportunities for agricultural and forestry productivity from new/alternative species becoming suitable</b>			
<b>Are the opportunities going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
No (Low confidence)	No (Low confidence)	No (Low confidence)	No (Low confidence)

### 3.10.3 Benefits of further adaptation action in the next five years (N9)

Currently crop breeding mainly focuses on yield and disease resistance and the multiple effects from climate change are not generally systematically considered, meaning there is a need for a more co-ordinated approach that includes both a wide range of potential future crop growth facilitators and stresses (e.g., disease, drought, heat, waterlogging etc.). More detailed scoping and investigation of opportunities is required that is also consistent with changing patterns of land capability and individual crop suitability across the UK. A major gap in knowledge and knowledge exchange appears to exist for opportunities for fruits, vegetables, and horticultural crops in a future climate, which would seem especially important because of the key role of these crops in human nutrition, including local availability and variety. Consumer surveys have suggested there is a significant unrealised demand for local produce, and more emphasis on new opportunities could have a key role in meeting that demand. As noted above, based upon the survey of non-traditional crops grown by smallholders in the Midlands (Kell *et al.*, 2018), there are also important food-cultural interactions with growing diverse local crops that could be further supported. In addition, new opportunities related to inter-cropping and agro-forestry require further systematic investigation in relation to improved understanding of different combinations in a wide variety of contexts, and the existing barriers that prevent increased uptake.

#### 3.10.3.1 Indicative costs and benefits of additional adaptation (N9)

The analysis of the wine sector (Watkiss *et al.*, 2019) found there were early low regret actions that could be introduced to increase the opportunity presented by a warming climate, as well as to reduce the risks associated with possible climate variability (particularly the risks to grape growth from cold snaps). The study also found a large number of no- or low-regret options from Europe for addressing climate variability that could be adopted in the UK (e.g., Neethling *et al.*, 2016). The research also undertook an initial analysis of the potential costs and benefits of additional early adaptation. This indicated that under a scenario where wine growers were able to realise the

benefits of climate change due to better information, and at the same time introduce adaptation measures to address potential variability risks, there would be very large economic benefits. The consideration of similar opportunities is less well characterised, but similar activities should be included for further investigation.

### 3.10.3.2 Overall urgency scores (N9)

<b>Table 3.31</b> Urgency scores for opportunities for agricultural and forestry productivity from new/alternative species becoming suitable				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	Further Investigation	Further Investigation	Further Investigation	Further investigation
<b>Confidence</b>	Low	Low	Low	Low

The primary constraint for adaptation decision-making at present is the limited information available (as consistent with the assigned low quality of evidence), therefore we identify this topic as an urgent priority for further investigation. Nevertheless, our view based on the evidence available is that there is an important role for policy in this investigation process, such as by providing increased support for adaptive innovation through field or stand trials, or new cropping systems, and to enhance knowledge exchange related to such initiatives to encourage greater uptake and collaborative learning.

#### Areas of focus:

- More systematic investigation is required, including a review of barriers to the market taking up the opportunities for new species, outreach activities and collation of existing and new knowledge on species and cultivars, and innovative cropping/silviculture systems.
- There is potential for grant-funding mechanisms in the new funding schemes for land managers that are replacing the Common Agricultural Policy to further support innovation and knowledge sharing related to these new opportunities based upon further trialling of the benefits.

### 3.10.4 Looking ahead (N9)

Particularly useful for this topic would be an inventory of changing distribution of crops/varieties/cultivars as an extension of the Defra and Scottish Government annual production census for agriculture and forestry, including geographic changes in distribution. This could also cover changes in the uptake of inter-cropping systems and other related novel practices. It would also be useful to obtain more information on changing climate suitability and climate resilience from crop breeding programmes, trials, and commercial programmes, such as through a co-ordinated knowledge exchange initiative. Another important source of evidence would be a robust assessment



of the potential for growing a wider range of crops than at present (considering both productivity and land suitability), in support of healthy food systems and also linking with the Net Zero agenda.

### 3.11. Risks to aquifers and agricultural land from saltwater intrusion (N10)

- Future risk to aquifers and agricultural land from seawater saline intrusion is expected to increase gradually with sea level rise and may be more pronounced during drought periods depending on any adjustment to water abstraction rates.
- Current risk at national scale is assessed as low at present and most likely to remain low in future (although potentially higher for England and Wales in a 4°C scenario by the 2080s). However, the scale of intrusion risk would significantly increase should a more extreme rate of sea level rise occur (a High++ scenario).
- No additional intervention is presently needed to manage current and future risk, however, there is limited evidence for this topic and further research on changes in exposure and vulnerability is recommended, especially as risk is more localised in some areas.
- England and Wales are assessed as needing 'Further Investigation', while Scotland and Northern Ireland have been assigned a 'Watching Brief' due to the lesser scale of risk exposure given present available evidence.

#### Introduction

This risk defines the threat that saline intrusion from sea level rise causes for coastal aquifers and agricultural land. A transition to saltwater or brackish water has important implications for availability of water resources and their use to support productive land use, depending on the scale and timing of intrusion. Our assessment of available evidence is that the risk is currently low at present and most likely to remain low in future unless a much greater rate of sea level rise was to occur (a High++ scenario) and therefore the scale of intrusion would significantly increase. Continuing current risk management procedures therefore would seem to remain adequate to adapt to the risk. However, evidence is rather limited for this issue and further research on changes in exposure and vulnerability is recommended, including in the context of the latest scientific data on sea-level rise. For Scotland and Northern Ireland this appears a lesser risk as the scale of exposure appears smaller (although evidence is even more constrained here) and continuation of a 'watching brief' is therefore probably more appropriate.

Links between this risk and either EU-exit or COVID-19 remain to be further established as there is no known evidence on these interactions.

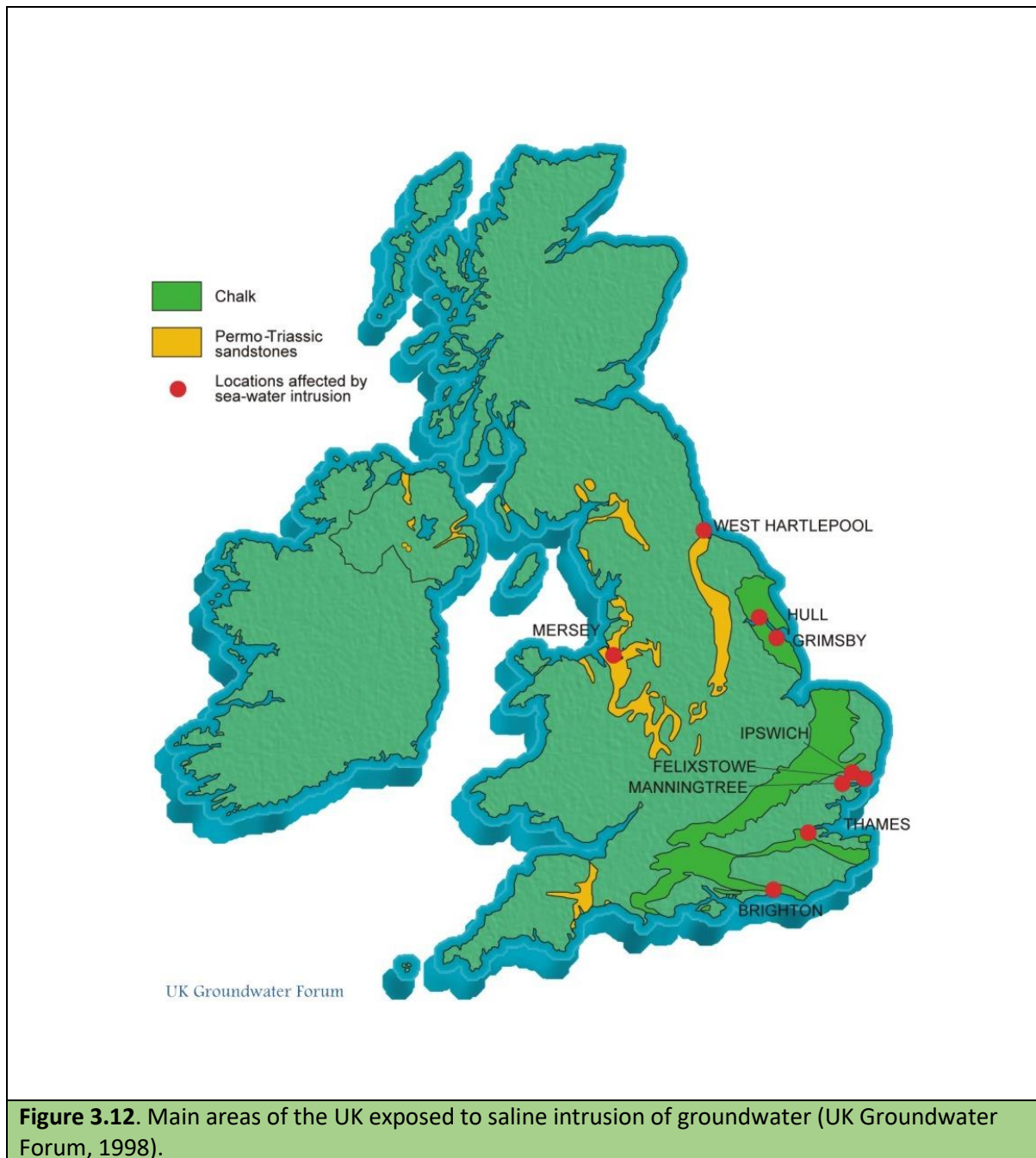
### 3.11.1 Current and future level of risk (N10)

#### 3.11.1.1 Current risk (N10)

Currently this is a localised risk in the UK. Saline intrusion can affect groundwater as a result of over-abstraction (via pumps, boreholes or wells). The hydraulic gradient from the land to the sea can be weakened, and sometimes reversed, by the removal of freshwater. Hydraulic gradients can also be disrupted where land elevation lowering has occurred due to drainage and subsidence (e.g., the Fens), which may involve pumping stations. Because sea water is denser than freshwater, the intrusion will (at first) occur in the lower parts of the aquifer, with the freshwater-seawater boundary moving landwards. The intrusion of salt water into coastal aquifers can impact on water availability in those districts, which can impact on agriculture. Some water abstraction also occurs seasonally in estuaries based upon the relative predominance of freshwater and saltwater (which follows a well-defined pattern based on tidal flows), and the abstraction regime is therefore designed to take account of salinity constraints.

Risks to coastal aquifers are a consequence of sea-level rise causing saline intrusion and from reduced summer rainfall and aquifer recharge, particularly for eastern and southern England where some aquifers provide public water supplies (e.g., Dungeness in Kent, which is underlain by the Denge gravel aquifer). This risk therefore requires balancing abstraction and recharge to prevent saline intrusion, as informed by detailed monitoring, and, if necessary, abstraction restrictions during drought periods. Abstraction for agricultural use through groundwater boreholes currently tends to be smaller scale compared to public water supplies.

The overall exposure to salinization of coastal aquifers for the UK is not known. An indicative map of exposure is provided in Figure 3.12 but this is dated and more detailed data would be required for a full national risk assessment. In addition, saline intrusion may occur through drift deposits, as notably in coastal areas of the Fens and East Anglia where shallow groundwater basins are below sea level. Our assessment is that this risk is a lesser issue for Scotland and Northern Ireland, both because the underlying geology means that surface water resources dominate over groundwater resources, and because relative sea-level rise to present has been generally lower in the northern UK due to local land uplift. Wales may be expected to have some localised exposure, but to a rather lesser extent than England.



Regarding impacts on water quality, 13 failures to meet good ecological status as notified under Water Framework Directive (WFD) reporting (Environment Agency; SEPA; NRW; DAERI) were attributed to saline intrusion in England and Wales, and 12 in Scotland in 2014. However, these make up a very small proportion (<1%) of total failures. Only one water company in southern England has identified constraints from salinization in its planning tables for sources and licensing agreements (although this is not a mandatory requirement), with 2 licenses affected (a total of up to 22.98 Ml/d, although the deployable output is lower: up to 15.36 Ml/d). Similarly, while the effects of water salinization on agricultural land currently remain localised, detailed risk mapping at national scale is not presently available. Areas of agricultural land exposed to surface flooding risks have been identified through topographic analysis (see Risk N6) but the more refined assessment required to

assess groundwater saline intrusion risks is usually only defined locally and requires detailed hydrogeological data.

### 3.11.1.2 Future risk (N10)

The magnitude of future risk is strongly related to the magnitude of sea-level rise and will also be influenced by shifts in hydraulic gradient related to changing precipitation patterns. In addition, the risk will be influenced by water abstraction rates in exposed areas; if these are not adjusted to allow for the increased risk and continue as before (or even possibly increase under some socioeconomic scenarios) then they are likely to significantly exacerbate the risk. However, with regard to public water supplies, the current abstraction strategy does already allow for seasonal variations.

Our assessment is that the future risk to aquifers is therefore expected to gradually increase with sea level rise and may be more pronounced during drought periods. As intense cyclonic conditions influencing storm surges most commonly take place outside summer months, their coincidence with previous drought conditions is relatively low. However, if drought conditions extend into the stormy autumn season, then the combined effect may produce a more extreme risk of intrusion. No evidence is available to identify exposure of new areas beyond those currently affected (primarily eastern and south east England) but it is possible that some water resource zones with high demand elsewhere in the UK may also experience a relative increase in risk. As sea level rise values are lower in Scotland and Northern Ireland, exposure is lower, and also public and agricultural water supplies there have a smaller reliance on coastal aquifers.

Although UKCP18 has provided median and upper-end sea-level rise projections that are higher than UKCP09, this increase is by itself not expected to significantly change the magnitude for this risk based on current evidence of exposure and sensitivity. An exception to these findings would occur if an extreme High++ future climate scenario was to be realised. As discussed in Chapter 1 (Slingo, 2021), extreme sea level rises reaching 2m by 2100 cannot be excluded as a possibility despite their much smaller likelihood based on current evidence. However, there is currently no evidence to identify how big a difference such a H++ scenario would make in terms of exposure and implications for public water supply and agricultural land.

With regard to aquifers, in a scenario consistent with approximately 4°C global warming at the end of the century<sup>21</sup>, the recharge season for groundwater may on average become shorter in future, with greater amount of recharge “squeezed” into fewer months (Mansour and Hughes, 2017; Mansour *et al.*, 2018). Although groundwater recharge continues under this future scenario, it also becomes more irregular (‘lumpy’) and if precipitation inputs fail for one of these critical recharge months, then the aquifer may become more vulnerable to increased drawdown, especially if abstraction rates are not reduced in response. However, no known research has investigated this issue yet in the context of implications for saline intrusion.

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<sup>21</sup> UKCP09 perturbed-parameter ensemble with the HadRM3 regional climate model driven by the SRES A1B scenario

#### 3.11.1.3 Lock-in (N10)

There are lock-in risks but only if abstraction rates continue as present, or increase, and are not adjusted to the changing climate-related exposure from sea-level rise.

#### 3.11.1.4 Potential thresholds (N10)

There are thresholds associated with sea-level rise, although the critical value be dependent on local contexts. There is also likely to be a threshold value for safe abstraction, as defined relative to local precipitation rates and the pattern of groundwater recharge.

#### 3.11.1.5 Cross-cutting risks and inter-dependencies (N10)

Abstraction rates will be influenced by demand for water, both through the public water supply, and to sustain agricultural production (Risk N7). Reduced water quality (and hence supply) may impact on water availability for different uses, including agriculture, and may also have consequences for freshwater biodiversity (Risk N11). An important interaction may also exist with coastal zone management and potential further implementation of managed realignment schemes (see Risk N17), because, by altering the salinity regime in estuaries, these may modify the saline intrusion risk in that location. However, presently there is no evidence to show the scale of this interaction.

#### 3.11.1.6 Implications of Net Zero (N10)

No evidence was identified. Potentially, the impetus in the Net Zero scenario to intensify agricultural production may increase water demand in at-risk areas and therefore increase the frequency of salinity intrusion. This could then impact on water availability and production capability, although problems could be avoided through good planning and management.

#### 3.11.1.7 Inequalities (N10)

No evidence for impacts on inequalities were identified in relation to climate change risks to aquifers and agricultural land from saltwater intrusion.

#### 3.11.1.8 Magnitude scores (N10)

Magnitude categories are based on expert judgement of existing and expected impacts on water quality due to limited quantitative data. Risk magnitude (national scale) is assessed as low at present and continuing as low for the future climate projections. The exception is for 4°C in the 2080s, for which the combination of climate change and socioeconomic factors means we have identified risks in England and Wales as of 'unknown' magnitude, with an increased possibility that magnitude may increase from low to medium. For Scotland and Northern Ireland, the lower level of exposure suggests that a low-risk magnitude would still apply. Confidence in this categorisation is higher than may be expected based upon evidence of impacts because it would be expected that, if the current risk was higher, more negative impacts would have been detected and reported through monitoring data and resource surveys (e.g., water company reports). We also use this current absence of impacts when assessing confidence in risks from future scenarios. It should be noted, however, that if an extreme High++ sea-level rise scenario were to develop (i.e., higher than the assumed

‘reasonable worst-case scenario’), as cannot be excluded especially in a pathway to 4°C global warming at the end of the century, then this risk would likely be in a higher magnitude category due to increased exposure.

**Table 3.32** Magnitude scores for risks to aquifers and agricultural land from saltwater intrusion

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Low  (High confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Unknown
<b>Northern Ireland</b>	Low  (High confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)
<b>Scotland</b>	Low  (High confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)
<b>Wales</b>	Low  (High confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Unknown

### 3.11.2 Extent to which current adaptation will manage the risk (N10)

#### 3.11.2.1 Effects of current adaptation policy and commitments on current and future risk (N10)

Abstraction is regulated by government policy and at present is licensed by the regulatory authorities in each country in accordance with the water quality requirements of the Water Framework Directive. As discussed above, this acts to identify and report impacts on water resources in combination with water company plans. In general, although there remain important uncertainties, vulnerable aquifers are known from their hydrogeological properties and can be monitored, and alternative resources identified. Measures to manage the risk are already in use and will require further review based upon ongoing monitoring referenced against ongoing climate change. The licensing system is currently being reformed which is expected to provide improvements in the sustainability of the resource. The gradual transitional time of saline intrusion of aquifers (even with higher rates of sea level rise) should provide time to adapt, except perhaps in the extreme case of a High++ scenario (e.g., due to accelerated mass loss from ice sheets, see Chapter 1: Slingo, 2021).

Our assessment is that adaptation is therefore presently occurring through existing policy frameworks, although not explicitly referenced to climate change. This is more defined for England and Wales (or more specifically, for specific regions based upon hydrogeology) and to a rather lesser extent for Scotland but this would be consistent with an expected lower risk exposure. In addition to an assumed continuation of water body status reporting consistent with commitments previously made for the EU WFD, monitoring and responses may be activated through nature conservation legislation. For example, in Wales, efforts to mitigate saltwater intrusion are in part delivered through policy related to the Conservation of Habitats and Species Regulations 2017. In Scotland, SEPA and Scottish Water measure saline levels as part of their formal water quality testing and abstraction management programmes so any trends are expected to be detected using existing programmes of monitoring. A different situation exists in Northern Ireland where some water bodies are shared as international transboundary resources that are managed with the Republic of Ireland, but again there are no known issues at present regarding saline intrusion for these water bodies. At the time of assessment, there are uncertainties regarding the future status of groundwater management between Northern Ireland and the Republic of Ireland regarding policies following UK exit from the EU (previously defined through WFD obligations), highlighting that a transboundary groundwater agreement may be beneficial to co-ordinate responses.

#### 3.11.2.2. Effects of non-Government adaptation (N10)

Water companies currently adjust their abstraction regime based upon knowledge of the risk of saline intrusion from monitoring, therefore adaptive capacity already exists. Agricultural abstraction is more localised and controlled through the licensing system including licenses of right (issued in perpetuity, linked to assumed 'grandfather rights' etc.) and time-bound licenses (subject to regular review) (Parliamentary Office of Science & Technology, 2017). Not all of the allocated licensing rights are currently used and if used to their fullest extent may cause additional problems in some locations. Regular update of license agreements could be adjusted to manage the risk of salinization in exposed areas.

Farmers experiencing local salinisation problems have in some locations adapted to the risk by digging 'seepage pits' to rapidly abstract freshwater lenses. Alternatively, some crops can cope with irrigation by brackish water and can still provide viable produce (e.g., potatoes). However, the long-term effects of these strategies are unknown.

#### 3.11.2.3 Barriers preventing adaptation to the risk (N10)

Increased agricultural water demand and groundwater abstraction may increase the risk of groundwater intrusion unless appropriately regulated. Similarly, increased household water demand (either per capita demand or through new housebuilding) in some locations may also place additional stress on groundwater reserves, leading to increased intrusion risk, unless regulated.

#### 3.11.2.4 Adaptation shortfall (N10)

The risk to aquifers and agricultural land from saline intrusion is low at present (based upon existing reporting) and most likely to remain low in the future (extrapolated from existing risk exposure), except in instances of more extreme sea-level rise (most notably a High++ scenario). Additional

stresses from human pressures (see below) also need careful monitoring to understand the combined risk from climate and socioeconomic change. Continuing current risk management procedures therefore appear adequate to maintain risk at a low level by 2100 as long as monitoring efforts continue, although some local areas may experience an increased exposure especially during drought conditions. Confidence is medium in this assessment based on current reporting, but some limitations can be identified in existing knowledge both regarding the changing level of exposure and the intrinsic vulnerability of different groundwater systems and their users to changes in risk factors.

### 3.11.2.5 Adaptation Scores (N10)

<b>Table 3.33</b> Adaptation scores risks to aquifers and agricultural land from saltwater intrusion			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Yes	Yes	Yes	Yes
(Medium confidence)	(Medium confidence)	(Medium confidence)	(Medium confidence)

### 3.11.3 Benefits of further adaptation action in the next five years (N10)

Increased pressure on aquifers at risk of saline intrusion from agricultural water demand could be alleviated by use of alternative water resources. For example, better storage and use of excess winter rainfall and other methods to maximise sustainable use of surface water resources (e.g., rainwater harvesting and on-farm reservoirs) could act to conserve groundwater resources at a sustainable level and mitigate against saline intrusion (although also noting that some surface water is essential for groundwater recharge). Policy guidance and water abstraction licensing arrangements would need further refinement to incentivise such arrangements as consistent with regular review of regulatory limits.

As the key climate change drivers for this risk are relative sea-level rise and seasonal precipitation regimes, this risk topic would be an appropriate one to further investigate through the operational use of adaptation pathways. This would require enhanced collation and use of knowledge on the relationship between climate change drivers and safe abstraction rates at specific locations. By identifying and defining trigger points in the existing policy review cycles, linked to both the rate of sea-level rise and the recharge rate of the vulnerable groundwater resource (as linked to changing precipitation patterns), different pathways for achieving sustainable abstraction could then be defined that better recognised future uncertainty.

#### 3.11.3.1 Indicative costs and benefits of additional adaptation (N10)

There are some studies which include the impacts (in economic terms) of climate change on saltwater intrusion (e.g., see Brown *et al.*, 2011; Hinkel *et al.*, 2014), but these tend to be aggregated alongside flood damages, and are low in comparison, and these studies do not assess the costs and benefits of adaptation for salt water intrusion. There are also some case studies, but these tend to



focus on urban areas, where there are very high economic costs (from contamination) and thus very different benefit to cost ratios. There is therefore a low-regret action to investigate this impact further (i.e., the value of information relating to saltwater intrusion adaptation options for agricultural land), and a more iterative approach which includes monitoring is generally considered a low regret option. There are examples of adaptation options to prevent vulnerable aquifers from saline intrusion, including saltwater intrusion barriers and freshwater injection (Zhu *et al.*, 2010) and cost-benefit information exists for these measures from countries with greater saline intrusion problems. These generally show when aquifers are in use, measures have economic benefits when compared to subsequent water treatment and restoration costs after contamination occurs.

### 3.11.3.2 Overall urgency scores (N10)

<b>Table 3.34</b> Urgency scores for risks to aquifers and agricultural land from saltwater intrusion				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	Further Investigation	Watching Brief	Watching Brief	Further Investigation
<b>Confidence</b>	Low/Medium	Low	Low	Low/Medium

Given the projected low levels of future risk and adequacy of current risk management procedures to adapt to the risk, continuing with current procedures for the next 5 years until the next CCRA seems suitable. However, because risk is localised in specific areas, and because some important knowledge gaps have apparently been identified, England and Wales are identified as areas of the UK that would benefit from 'Further Investigation' to provide additional clarification on exposure and vulnerability issues. Scotland and Northern Ireland are assigned a 'Watching Brief' assessment due to the lesser scale of risk exposure, although here current evidence is also more limited (presumably consistent with assumed lower exposure and vulnerability to this risk).

Areas of focus:

- Liaise with water companies and water users to further investigate spatial and temporal patterns in risk exposure and vulnerability.
- Continue to monitor and report on impacts for aquifers to assess whether risks are increasing.
- Develop forward projections based upon different climate change and socioeconomic scenarios to assess robustness of regional and national resources and implications for adaptive resource management.

### 3.11.4 Looking ahead (N10)

An improved national assessment of risk exposure for vulnerable aquifers under different UKCP18 projections would be beneficial in advance of CCRA4, and subsequent work to understand associated implications for public water supply and agricultural demand.

### 3.12 Risks to freshwater species and habitats from changing climatic conditions and extreme events, including higher water temperatures, flooding, water scarcity and phenological shifts (N11)

- Risks from reduced water availability and higher water temperatures will increase the degradation of freshwater habitats and compromise the viability of some freshwater species.
- The magnitude of current and future risks is judged to be medium in the 2050s on pathways to both 2°C and 4°C global warming by the end of the century. By the 2080s, it remains as medium on the 2°C warming pathway, but increases to high magnitude on the 4°C warming pathway.
- This risk has been assessed as needing more action due to the incomplete base of evidence for climate impacts on freshwater ecosystems at present, and the shortfall in adaptation measures that exist.

#### Introduction

Freshwaters provide the UK with a wide array of socioeconomically important ecosystem services, including water supply (for drinking, agriculture, and industry), peat extraction, pollution removal, and recreation (e.g., fishing and tourism). The asset value of freshwater services to the UK (2014-2015) has been estimated at approximately £39.5 billion (Office for National Statistics, 2017), although the estimate should be interpreted as the minimum value of the habitat, as it does not include all relevant ecosystem services since some cannot be measured. Underpinning these important assets and services are biodiversity and ecological processes that are sensitive to climate change. While CCRA2 identified freshwater habitats as being particularly vulnerable to reduced water availability in the face of climate change, freshwater species and biodiversity are highly sensitive to the direct and indirect effects of temperature as well.

The potential impacts of climate change on freshwater are numerous and complex. Direct effects of changes in temperature occur through species behavioural and physiological responses. Indirect effects occur when temperature change impacts species interactions and habitat features, which in turn affect, or can cause the loss of, sensitive species (Moss, 2014). For obligate aquatic species (e.g., fish, plankton) water temperature is of direct relevance to climate change impacts. However, for other species, air temperatures will also be important e.g., water birds. Furthermore, migrant species will likely be affected by temperature change throughout their migratory route, including wintering and breeding grounds.

In addition to impacts on biodiversity, higher temperatures can directly increase the possibility of water quality problems through increasing the rates of biological and chemical processes, especially algal growth rates and nutrient cycling (Charlton *et al.*, 2018; EA, 2019b). However, indirect effects are also possible, through temperature effects on lake mixing patterns that in turn influence nutrient cycling and algal growth (Radbourne *et al.*, 2019). Additional complexity arises because climate

change interacts with other stressors, such as nutrient enrichment, to affect the state of freshwater ecosystems.

A recent assessment of climate-driven thresholds (Jones *et al.*, 2020) focused on four potential risks at UK scale: algal blooms in lakes, algal blooms in rivers, loss of habitat for sensitive fish species, and changes in the composition of lake plankton populations. Given currently available evidence, economic valuation of risk was possible only for algal blooms in lakes. Even so, the costs of this risk alone, based on a single UKCP18 model variation, were projected to increase from £173 million at baseline (2001-2010) to £295 million under a scenario of 2°C global warming and £481 million with 4°C global warming<sup>22</sup>. Given the lack of suitable data to place a monetary value on many other climate change effects, we must view these figures as a minimum estimate of economic impact.

At present, given the available evidence, the magnitude of current and future risks is judged to be medium in the 2050s on pathways to both 2°C and 4°C global warming by the end of the century. By the 2080s, it remains as medium on the 2°C warming pathway. However, with increasing volumes of evidence on specific impacts and sensitive species, this risk could increase. Thus, the magnitude is scored as high for the 2080s with 4°C global warming, due to the likelihood of greater changes in temperature, river flows and water quality under this scenario. Given the currently incomplete knowledge of climate impacts on freshwater ecosystems, and the current shortfall in adaptation measures, there is a need for more action, combined with further investigation on the scale of risk and effectiveness of these measures.

### 3.12.1 Current and future level of risk (N11)

Climate change can impact freshwater habitats and species both directly (e.g., species growth and survival responding to temperature change and alterations to flow regimes) and indirectly (e.g., effects on species manifest through their interactions with predators and competitors, or through climate effects on habitat conditions). It is therefore necessary to consider the evidence for climate impacts on physical, chemical and biological features of fresh waters. In general, freshwater species may respond to climate change through changes in their abundance, life history characteristics, distribution, and seasonal behaviour.

Note: currently available evidence is not sufficient to allow us to report on the current and future level of risk and opportunity for each UK country separately.

#### 3.12.1.1 Current risk (N11)

Given the multifaceted nature of climate change effects on freshwater habitats and species, recent evidence is organised into a series of impact types.

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<sup>22</sup> UKCP18 regional model driven by a global model with the RCP8.5 emissions scenario, reaching 2°C global warming in 2025-2034 and 4°C global warming in the 2060s. This rapid rate of warming is a low-probability, high-impact scenario but can be used to infer impacts of the same levels of warming reached at later dates.

### 3.12.1.1.1 Impacts on thermal regime

An important consideration for freshwater climate impacts is the relationship between observed air temperature change, and corresponding changes in water temperature. There is not a simple 1:1 relationship between these measures (Defra, 2014). Recent modelling work, using current stream and air temperature data from across Scotland, showed that this relationship is spatially and seasonally variable, dependent on local topography and land cover (Jackson *et al.*, 2018). For example, at maximum air temperatures of 25°C, maximum water temperatures under 100% riparian woodland cover are estimated to be approximately 2 °C lower than under 0% cover. Water temperature and the thermal effects of riparian shading may themselves depend upon large-scale atmospheric phenomena. Analysing ~1 million temperature records across England, Wilby and Johnson (2020) showed that summer river water temperatures were especially sensitive to variations in the North Atlantic Oscillation (NAO) in northeast and west England, and at sites >300m elevation. In a parallel analysis of data from the Loughborough University Temperature Network, they also showed that the NAO can influence the thermal effects of riparian shading, with temperature differences between open and shaded sites being greater under a positive NAO. The sensitivity of river water temperatures to air temperature is also influenced by hydrometric area and elevation. Work originating beyond the UK further supports the likelihood of spatially-variable water temperature responses to air temperature change. For example, high groundwater contributions to streamflow (high baseflow) in some systems may serve to dampen stream water temperature change (Carlson *et al.*, 2017, Briggs *et al.*, 2018). Global-scale studies (including UK fresh waters) show similar among-habitat variability for standing waters: O'Reilly *et al.* (2015) found that trends in lake surface water temperatures can exceed or fall below coincident air temperature trends. An investigation into the salmonid recruitment crash in Welsh rivers found that that a combination of high water temperature during spawning, and low water temperature together with high flows during emergence might have led to the 2016 juvenile salmon crash, but that trout were less affected, although recruitment was poor (Gregory *et al.*, 2020).

Multi-decadal data sets for UK lakes are rare, but exceptionally long-running data from four “sentinel” lake basins in Cumbria, collected by the UK Centre for Ecology and Hydrology, show that 4 of the 5 warmest years since 1945 have occurred post-2000 (Muchan, 2020). Furthermore, recent analysis of warm-season lake surface water temperatures in 127 European lakes (including some from the UK) demonstrated a warming trend of  $+0.39 \pm 0.03^{\circ}\text{C decade}^{-1}$  in the 1995-2019 period (Blunden and Arndt, 2020), while average water temperature changes of  $+0.34^{\circ}\text{C decade}^{-1}$  were reported for 235 globally-distributed lakes between 1985 and 2009 (O'Reilly *et al.*, 2015). Previous analyses of river water temperatures across England and Wales (1990-2006), reported in CCRA2, also showed that, on average, mean water temperatures have increased by  $0.03^{\circ}\text{C y}^{-1}$  (Orr *et al.*, 2014).

### 3.12.1.1.2 Ecological effects via altered river flows and water quantity

CCRA2 identified freshwater habitats as being particularly vulnerable to reduced water availability in the face of climate change. The impacts of drought can fundamentally change freshwater biodiversity. For example, in river macrophyte communities, resident species can be eradicated, allowing more opportunistic species to establish (Lake, 2011). Aquatic plants are of fundamental

importance to such ecosystems; when they die, organic material is deposited on the riverbed and brink, serving as a high-moisture refuge for other biota during drought conditions (Lake, 2011). Drought can also lead to a loss of horizontal, longitudinal and vertical habitat connectivity, while after a drought, sediments and nutrients are washed into the river and sulphates can be released from soils (Dobel *et al.*, 2019). Drought or low flow conditions will also reduce the dilution of pollutants, as well as nutrient inputs from sewage treatment works, which can lead to eutrophication (see below).

In addition to water scarcity itself, drought also leads to risks associated with water temperature. Under low-water conditions, water temperatures in pools can surpass the upper thermal limits of salmonid species, resulting in thermal stress (Elliott and Elliott, 2010). High temperatures during periods of water scarcity in summer 2018 led to an order to stop fishing in the River Test in Hampshire, England (Environment Agency, following the recommendation that catch and release angling is not practiced at mid-morning water temperatures in excess of 18°C). During 2018 there were localised fish kills in UK rivers resulting from associated de-oxygenation events (Dobel *et al.*, 2019).

As discussed in previous CCRA, for some catchments that have extensive areas of high ground, most notably in the Scottish Highlands and Cairngorms, the changing pattern of snow cover (extent and depth) can have an influence on hydrology and ecology. There is good evidence for declining snow cover in the British uplands, although there is high interannual variability and significant spatial and altitudinal relationships related to prevalence of large-scale atmospheric circulation patterns including the North Atlantic Oscillation (Kay, 2016; Brown, 2019). There is also good evidence that for snowmelt-sensitive catchments, reduced snow cover means that maximum peak flows tend towards occurring earlier in the winter season (rather than spring), with simulation models showing this relationship extends into the future (Bell *et al.*, 2016). This reduction in snow cover storage may also produce a more flashy hydrological regime and potentially higher peak flows due to more direct runoff in sensitive catchments, but this will also be strongly dependent on other changes in seasonal precipitation amounts for that catchment. In terms of ecological effects, the evidence is weaker: severe floods can damage important fish spawning grounds, notably for salmonids, but fish have also been negatively affected by a range of other pressures that have impacted on spawning.

#### 3.12.1.1.3 Water quality

Climate change impacts on water quality can impact biodiversity, the provision of clean water for consumption and associated water treatment costs, and the recreational potential of fresh waters. There is great potential for patterns of nutrient loading and enrichment to be impacted through climate driven changes to nutrient transport and biogeochemical processing within water bodies (Defra, 2014), with resulting impacts on species and habitat conditions. The complex interaction between water temperature and water quality is exemplified by a recent pan-European analysis (including data from numerous UK sites), which showed that, while rising temperatures could affect water quality by stimulating the growth of potentially-toxic “blue-green algae” (cyanobacteria), these effects vary greatly among lake types (varying in geographic location, water colour, alkalinity and mixing regime, Richardson *et al.*, 2018). Noting such dependencies, CCRA2 suggested that more action is needed to reduce pollution and improve the ecological condition of wetland habitats

through encouraging the wider uptake of management practices to help tackle the impact of interacting stressors. There are strong financial, as well as environmental, reasons for prioritising the restoration of water bodies.

To date, progress on improving the water quality and ecological condition of UK freshwater habitats has been mixed. The percentage of designated freshwater sites in favourable condition is improving, though freshwater SSSIs only represent approximately 8% of the total area of freshwater habitats in England (CCC, 2019b). Available data suggest that, between 2009 and 2019, there was little change in the overall number of surface water bodies in the UK awarded high or good ecological status according to the Water Framework Directive (WFD) (35-37% waterbodies, Defra, 2020a). In Northern Ireland, there has been a significant decline in lake status as part of WFD reporting since 2018. In 2018, 5 of the 21 lake water bodies were classified as ‘good’ or better and 16 lake water bodies were classified as ‘moderate’ or worse. In 2020, only 1 of the 21 lake water bodies were classified as ‘good’ or better status and the remaining 20 lake water bodies classified as ‘moderate’ or worse (DAERA, 2020).

Though much research has been conducted on the impacts of climate change on nutrient delivery and cycling, we recognise that there are many additional pollutants that could impact upon water quality and ecological state (e.g., organic pollution, ammonia, nanoparticles, metals, microplastics). The interdependencies between climate change and the impacts of these pollutants are worthy of further investigation.

#### 3.12.1.1.4 Species abundance and distribution

Recent evidence suggests that climate change is already affecting the abundance and distribution of freshwater species throughout the UK. For example, analyses of long-term (1981-2005) invertebrate data from the Llyn Brianne catchment in Wales revealed long-term declines in invertebrate abundances, and some local extinctions, that are attributable to warming (Jones *et al.*, 2013). Such impacts may be mediated by dissolved oxygen concentrations (Verberk *et al.*, 2016). Temperature can also affect population growth and body size in freshwater animals, including top predators like pike (Vindenes *et al.*, 2014), and can have cascading effects through food webs (Edeline *et al.*, 2016). Furthermore, in the UK, the small wintering population of smew (*Mergellus albellus*) is being negatively affected by increasing winter air temperatures and may be at risk of loss here, due to the species’ redistribution in response to climate change (Pavón-Jordán *et al.*, 2015). However, the UK is important for the species when winters in the central and north eastern part of its range are severe.

However, freshwater species are responding to a complex array of interacting stressors (Birk *et al.*, 2020), which may exacerbate, dampen, or dominate climate change impacts. An analysis of family-level distributions and nationwide trends in prevalence of macroinvertebrates, using data for 1991–2011 from >2300 rivers across England and Wales, showed that longer-term changes in prevalence were linked to water quality (concentrations of the nutrients nitrate and phosphate and overall organic loading), with little evidence of the influence of increasing water temperatures (Vaughan and Ormerod, 2014). For example, the small northward expansion of the range of many taxa was accounted for by large improvements in water quality in northern England. However, shorter-term

variations were linked to water temperature and nutrient concentrations. In fact, it has been suggested that water quality improvements across England and Wales have aided in offsetting the impacts of 0.64°C of warming on macroinvertebrate communities (Vaughan and Gotelli, 2019). As noted by the authors of this study, though, our potential to mitigate against climate impacts through water quality improvement is finite.

#### 3.12.1.1.5 Phenological shifts

Shifts in the seasonal timing of biological events (e.g., migration, breeding, flowering) are widely accepted to be part of the ecological “fingerprint” of climate change. These shifts are of concern given the potential for important species interactions to be disrupted, with consequences for ecosystem structure, function, and service provision. Broad-scale seasonal shifts are already apparent across the UK, based upon the analysis of long-term records (Thackeray *et al.*, 2010; 2016).

As a more specific example, the timing of salmon migration in rivers has been found to be correlated with freshwater temperatures up to about 10°C, levelling off at higher values (Otero *et al.*, 2014). In Scotland, the day of the year by which 25% of smolts have migrated has advanced by about 1.5 days per decade over the last 47 years (Malcolm *et al.*, 2015). Climate impacts upon Scotland's Atlantic salmon populations are of both national and international importance, since these stocks account for approximately 75% and 30% of estimated UK and European salmon production (pre-fishery abundance) respectively (ICES, 2016). Similarly, fry emergence dates for brown trout are affected by stream water temperature, becoming earlier under warmer conditions (Elliott and Elliott, 2010). Other climate-sensitive environmental factors can also have an effect on seasonal timing. For example, earlier Atlantic salmon migration was found to occur when river flows were low, but increasing (Otero *et al.*, 2014).

Temperature increase could also affect the seasonal behaviour of land-locked fish populations. Rising water temperatures in Windermere, England's largest lake, are associated with a shift towards earlier perch spawning (Thackeray *et al.*, 2013). However, changes in perch spawning have not kept pace with similar shifts in seasonal plankton food resources, with detectable effects on fish recruitment (Ohlberger *et al.*, 2014). The effects of shifting seasonality are relatively understudied in freshwater compared to terrestrial ecosystems (Samplonius *et al.*, 2021, but may have consequences for UK recreational fisheries.

Changing water temperatures also have the potential to fundamentally alter life cycles of aquatic insects. In the River Dove (English Peak District) the mayfly *Ephemera danica* was shown to shift from a two-year to one-year life cycle with greater growing degree day accumulation under warmer conditions (Everall *et al.*, 2015). It was inferred that this shift to a one-year life cycle would lead to an increased vulnerability of the insects to adverse weather, and reduced reproduction (fecundity). The shift in life cycle was not, however, observed in river reaches affected by cool groundwater inputs, which potentially act as thermal refugia.

### 3.12.1.1.6 Extreme events

Variability is a natural feature of freshwater ecosystem behaviour (e.g., predictable seasonal variations in flow, water level and temperature). However, there is concern that future increases in the frequency, intensity and duration of extreme events, beyond the range of natural variation, will have significant impacts on water quantity and quality, the structure of the physical environment, habitat availability and connectivity, and biodiversity (Jones *et al.*, 2013). The potential ecological outcomes of extremes are wide-ranging, depending on the nature of the extremes (e.g., flood, drought, heatwave), the space and time scales over which they occur, and the physical, chemical and biological features (including species traits) of impacted ecosystems.

Though there is great variability in the likely impacts of extreme events, documented examples are informative:

1. In October 2017, **Storm** Ophelia passed over the UK and increased wind energy at the surface of Windermere 25-fold, deepening mixing in the lake and causing an upwelling of cold, oxygen poor water (Woolway *et al.*, 2018). These upwelling waters flowed into the main outflow of the lake, the River Leven, resulting in a 48% reduction in dissolved oxygen concentrations. This example illustrates the profound effects that extremes can have on fresh waters, though it should be noted that these effects are likely to be highly variable among lakes and catchments (Stockwell *et al.*, 2020).
2. In 1997, a 1-in-100+ year **flood** occurred on the River Wansbeck, in Northumberland. This event damaged stands of emergent vegetation, including species such as the branched bur-reed (*Sparganium erectum*) and common club-rush (*Schoenoplectus lacustris*). Vegetation was uprooted by scouring flows and erosion that destroyed plant habitat, with consequent effects for organisms dependent upon this habitat (Jones *et al.*, 2013).
3. **Drought** conditions during the 1989-1992 period had a range of impacts upon chalk streams throughout south east England, including reductions in invertebrate abundance and species turnover in plants communities, which transitioned from non-aquatic to wetland and classic aquatic plants as flows resumed (Jones *et al.*, 2013). Recent large-scale outdoor mesocosm experiments suggest that frequent drought conditions may affect stability of stream ecosystem functions, with potential consequences for ecosystem service provision (Leigh *et al.*, 2019).
4. In 2016, in many rivers in England and Wales there was poor recruitment of juvenile salmonids, particularly salmon fry, which was thought to be caused by **unusually warm winter temperatures and extreme flows** which adversely affected spawning success (ICES, 2018).
5. **Thermopeaking** (rapid changes in water temperature) may occur in response to weather conditions. For example, sensor data from the River Dove (English Peak District) suggest that river temperatures can change suddenly in response to bright sunshine, heavy snowfall/melt, and intense rainfall (Wilby *et al.*, 2015). The most extreme temperature changes recorded in this study were +2.8 °C h<sup>-1</sup> for intense rainfall, -1.3 °C h<sup>-1</sup> for snow melt, and +1.2 °C h<sup>-1</sup> for intense solar heating. The impacts of such thermal extremes on freshwater biota require investigation.

While the impacts of extreme events can be profound, recovery can potentially occur quickly. The rate of population recovery varies greatly among species, according to their traits, but also depends on the availability of refuges in which species can survive extreme events, and habitat connectivity.



Furthermore, the combined effects of multiple anthropogenic stressors can hinder recovery from extremes (Jones *et al.*, 2013). Reported post-extreme recovery times are variable. Woodward *et al.*, (2015) report that, in the Glenfinish River (Ireland), a catastrophic 1986 summer flood triggered a 10-fold decline in invertebrate abundance. While most populations returned to their pre-disturbance state in less than 3 years, some took up to a decade to recover. It should be noted that the impacts of extreme weather are also context dependent. For instance, a study in Switzerland suggested that water temperature responses to heatwave conditions may be dampened in streams fed by snow melt, and receiving cool water from reservoir releases, when compared to lowland rivers (Piccolroaz *et al.*, 2018). To aid management and adaptation, we need to advance our understanding of what determines the sensitivity of UK freshwaters to extreme events.

#### 3.12.1.2 Future risk (N11)

UKCP18 climate scenarios suggest substantial increases in winter daily precipitation, both frequency and intensity, especially in western Britain (Chapter 1: Slingo, 2021). This has implications for river flows, flood risk and water resource management. Similarly, summers are projected to be hotter and drier, with the potential for more summer drought. In our view, these climate changes are likely to impact the state of freshwater ecosystems and water regulation services (water quality, water flows) in the future. Impacts on freshwater species and habitats will occur through increased temperatures, changes in patterns of rainfall and river flow, knock-on effects on nutrient inputs and cycling which will exacerbate eutrophication impacts, extreme events, and spatio-temporal changes in species distributions.

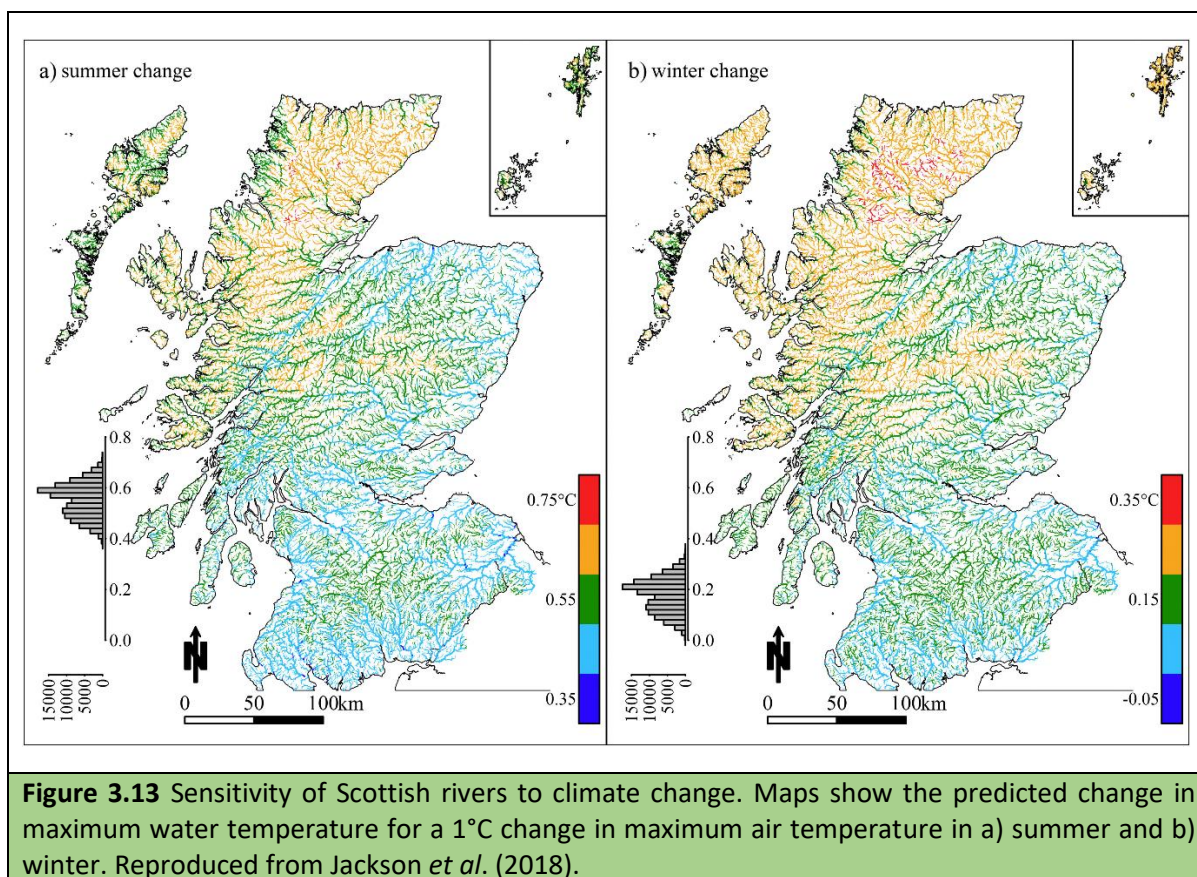
##### 3.12.1.2.1 Impacts on thermal regime

Climate change is projected to further impact the thermal regime of UK fresh waters. By combining global-scale satellite-derived lake temperature data and a climate change scenarios reaching approximately 2°C and 4°C global warming by 2100<sup>23</sup>), Maberly *et al.* (2020) estimated that between 12% and 27% of the world's larger lakes would shift to a thermal regime characteristic of present-day lower latitudes by 2080-2099. UK lakes were included in this study and are at risk of such a shift.

Future changes in water temperatures are likely to be spatially and seasonally variable, due to the impacts of local habitat features (e.g., riparian shading). Through statistical modelling of data from Scottish rivers, Jackson *et al.* (2018) showed that, as a result of such features, a 1°C rise in maximum air temperature could result in maximum water temperature increases of between 0.4 and 0.7°C in summer (Figure 3.13a). In winter, the same air temperature change resulted in water temperature changes of between 0.02 and 0.36°C (Figure 3.13b). River temperatures in the north and north west of Scotland and the Cairngorm Mountains were found to be most sensitive to air temperature variation. In Wales, high confidence has been attributed to changes in population dynamics of species as a result of higher water temperatures (Natural Resources Wales, 2020b) and such changes are consistent with current observation and are likely to occur across the UK in the future.

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<sup>23</sup> HadGEM2-ES model driven by RCP 2.6 and RCP 6.0 concentrations pathways



CCRA2 identified small, shallower lakes as being at risk from reduced circulation and larger, deeper lakes as being more sensitive to longer periods of thermal stratification reaching more deeply. International studies suggest that water temperatures are likely to increase in the future (although there are fewer published studies for the UK specifically), as a result both of increased air temperatures, as well as low flows in summer, with potentially negative impacts on sensitive species (Watts and Anderson, 2016).

### 3.12.1.2.2 Ecological effects via altered river flows and water quantity

Future alterations to flow regimes are likely to have consequences for freshwater species and habitats, as well as the water available for abstraction. Projected changes in river flows at Q95 (the flow that is exceeded by a river 95% of the time) are of the order of a 0% to 20% reduction across the UK by the mid-century in a pathway to approximately 2°C global warming by the late century<sup>24</sup>, except in the western highlands in Scotland, where flows increase (HR Wallingford, 2020). In a scenario of 4°C global warming in the late century, there is up to a 30% flow reduction in some areas, such as Wales, the Severn and Tweed river basins. Projected changes in river flows at Q95

<sup>24</sup> The HR Wallingford (2020) method defined the 2°C and 4°C pathways as the global warming levels (GWLs) reached late century (2070-2099) at the 50<sup>th</sup> percentiles of the UKCP18 probabilistic projections with the RCP2.6 and RCP8.5: 1.8°C and 4.2°C respectively. The former is near the centre of the lower CCRA3 scenario, and the latter is on the upper bound of the CCRA3 higher scenario (see Chapter 2: Watkiss and Betts, 2021). Late-century regional climate states were taken from the UKCP18 perturbed-parameter ensemble (PPE) of global 60km projections at those GWLs. Mid-century climate states were taken from the 60km PPE at the GWLs reached with RCP2.6 and RCP85 50<sup>th</sup> percentiles in 2040-2069. See HR Wallingford (2020) for details.

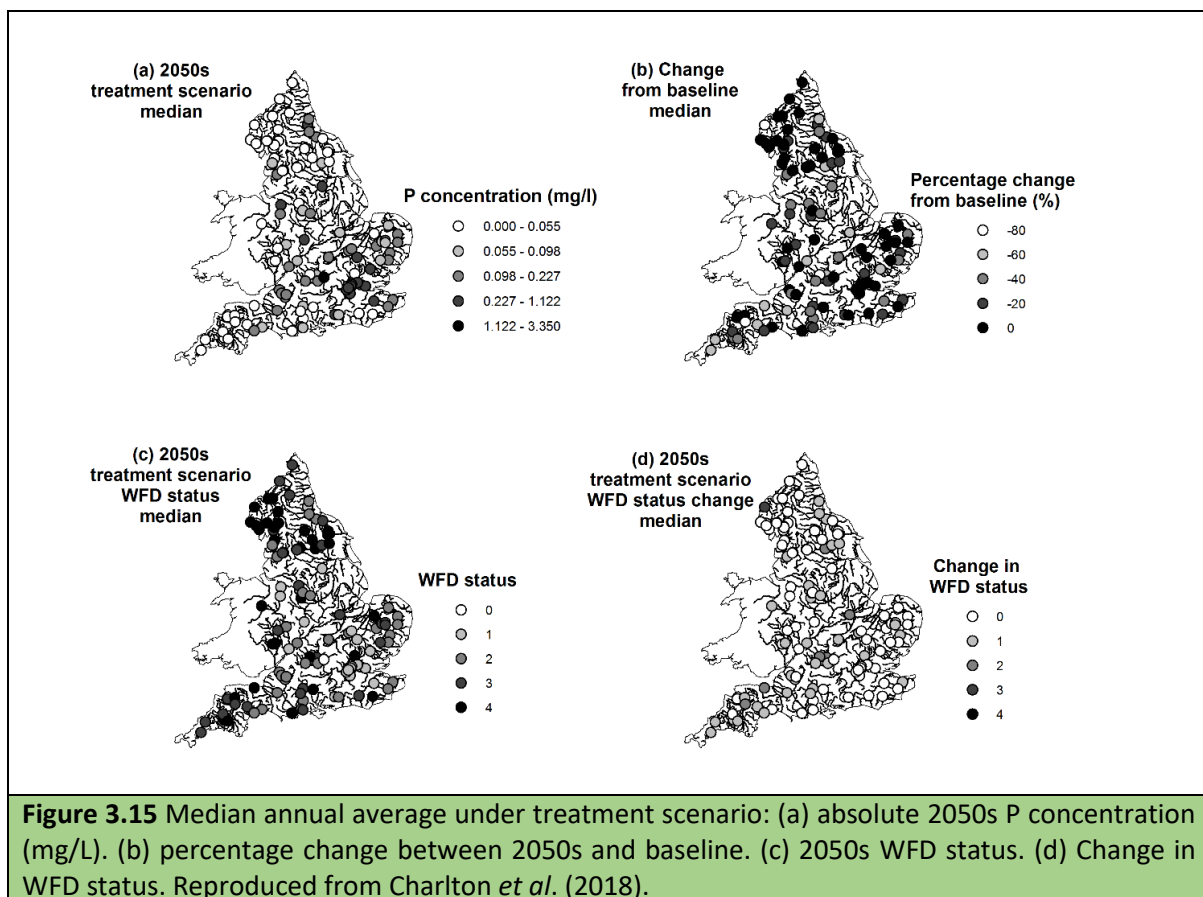
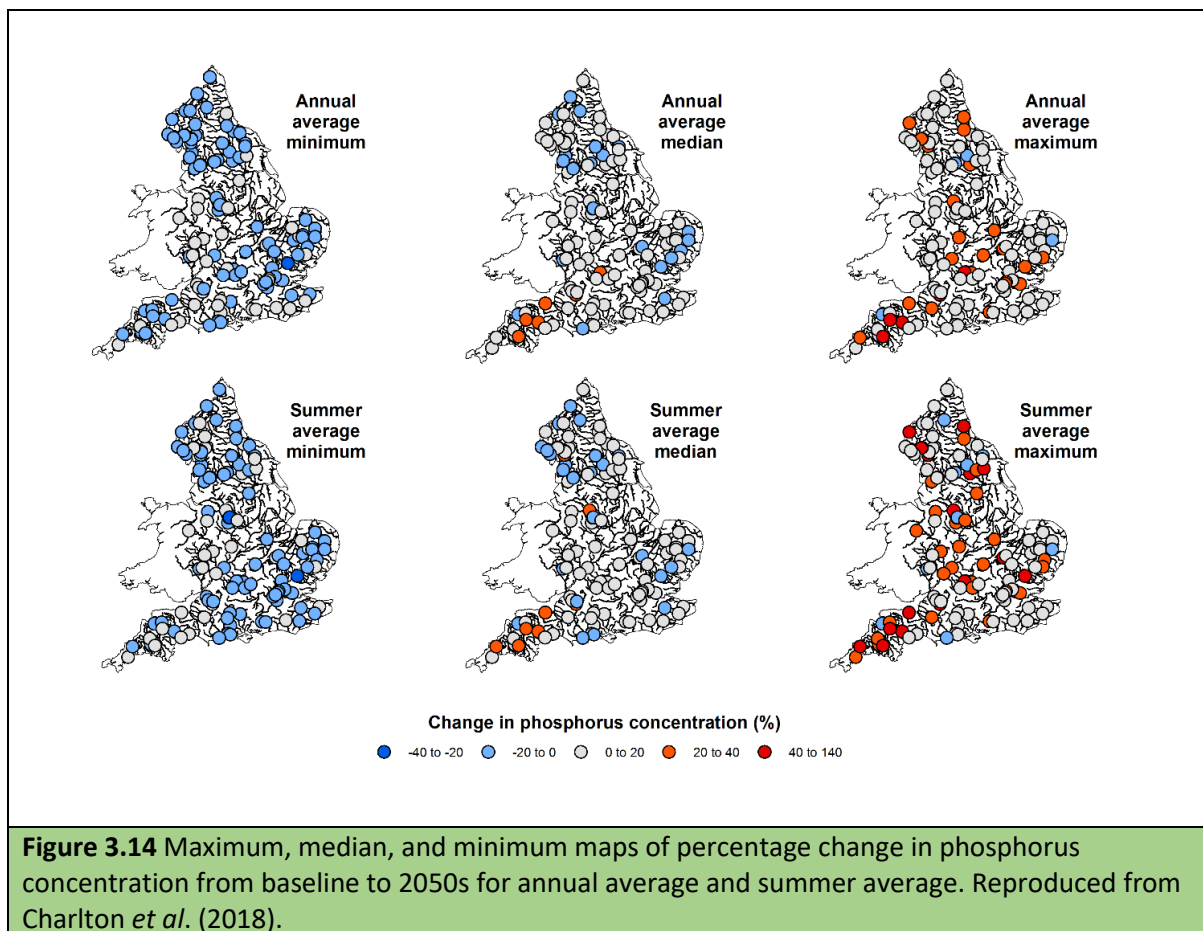
across the UK are of the order of 0% to 50% reduction by the late-century in the 4°C warming scenario.

Modelling based upon a combination of future climate change and socio-economic scenarios, suggests that over 50% of the European river network could change eco-hydrological type (i.e., ecologically relevant flow regime, defined by features of average flow and flow variability) by mid-century (Laize *et al.*, 2017). Indeed, it is projected that novel eco-hydrological river types may occur in some regions in future (9% to 18% of the river network), with the potential to support novel ecosystems.

While low flows are important in leading to possible loss of river connectivity, reduced nutrient dilution (section 3.12.1.2.3), and changes in freshwater biodiversity (section 3.12.1.1.2), in our view it is probably drought in a sequence of weather events (e.g., dry winter and then summer drought) that will have more significant impacts. Following drought, many species will recover, but there are possibilities of local losses or replacement by other species during recovery.

### 3.12.1.2.3 Water quality

Climate change could potentially cause water quality deterioration in rivers, because reductions in future flows could also reduce dilution of phosphorus inputs from wastewater treatment works, and lower the rate at which phosphorus is flushed from river reaches (EA, 2019). This, along with rising summer water temperatures, could stimulate algal growth. However, projected future changes in water quality remain highly uncertain due to the complex interaction between climate change and land use change, which will vary by catchment. Modelling of estimated in-stream total reactive phosphorus (TRP) concentrations for the 2050s under 11 climate change river flow scenarios, and under scenarios of both current and higher levels of sewage treatment in England, showed small, but spatially variable, increases in average annual TRP, with higher changes in summer (Figure 3.14, Charlton *et al.*, 2018, EA, 2019b). Improvements to point source sewage treatment (reductions in final effluent TRP concentrations to a maximum of 0.5 mg/L), though likely to result in lower river TRP concentrations, were found to be insufficient to improve the WFD phosphorus status for the majority rivers (Figure 3.15, see also EA 2019b), thus suggesting that sources of diffuse pollution from land use also need to be addressed.



Algal bloom risk has been modelled as a function of phosphorus concentrations, river flows, water temperature, and sunlight duration using the 11 Future Flows Hydrology (FFH) scenarios (Prudhomme *et al.*, 2013) driven by climate projections reaching 4°C global warming at the end of the century<sup>25</sup>, with a Load Apportionment Model (LAM) from UKCEH (EA, 2019c). This showed an increase in median bloom risk days from baseline (1961 to 1990) to the 2050s (2040 to 2069). The median increase was approximately eight days across 26 sites in England, from about 50 in the baseline period, although the maximum increase is up to 15 days. The change in risk is variable by the 2080s (2070 to 2098), with about 50% of sites showing reduced risk relative to the baseline period, resulting in a median increase of about 4 days and a maximum of up to 16 days. This variability is a function of flow variability, water temperature and sunlight duration, with the latter two seeming to be particularly important. The recent CCC thresholds project (Jones *et al.*, 2020) also estimates an increasing occurrence of temperatures that would stimulate algal blooms, assuming sufficient nutrient availability, across the UK (see below).

Using a model cascade, Bussi *et al.* (2016) projected likely impacts of a combination of changing climate and land management on phytoplankton concentrations in the River Thames. Specifically, the study suggests that a combination of reduced precipitation and rising air temperature in the future, coupled with increased conversion of land to intensive arable agriculture, is likely to result in increased phytoplankton (especially cyanobacteria) growth in the Thames. However, catchment-scale phosphorus mitigation strategies (reduced fertiliser application and enhanced wastewater treatment) could offset climate driven increases in phytoplankton growth.

Hydrological modelling for the Thames and Yorkshire Ouse using the CLASSIC model driven by projections of approximately 3°C and 5°C at the end of the century<sup>26</sup> suggested that by the 2080s, lower river flows in all seasons apart from winter could lead to longer residence times (by up to a month in the Thames). Nutrient, organic and biological contaminant concentrations could be elevated by 70–100% pro-rata (Johnson *et al.*, 2009) assuming sewage treatment effectiveness remains unchanged. In addition to stimulating phytoplankton growth, these changes could also result in an increased risk of human exposure to enteric pathogenic microbes, though there is considerable uncertainty regarding the magnitude of this risk, and the specific pathogens that are most likely to increase (see also Chapter 5: Kovats and Brisley, 2021).

Scenario modelling of lake ecosystems suggests that climate-driven increases in water temperature, and changes in mixing depth, can lead to increased algal growth and water quality deterioration (Gray *et al.*, 2019). However, the impacts of climate change on algal bloom magnitudes, and the dominant bloom forming species, will be mediated by important interactions with changing nutrient concentrations and cycling (Elliott *et al.*, 2016, Radbourne *et al.*, 2019) and thus by land and wastewater management.

Water quantity and quality will together influence the effects of climate change on water supply. Recent water resource modelling for the Thames catchment, under multiple climate, land-use and water demand scenarios (Mortazavi-Naeini *et al.*, 2019), projects substantially reduced water supply

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<sup>25</sup> UKCP09 HadRM3 regional climate model perturbed-parameter ensemble with the SRES A1B scenario

<sup>26</sup> UKCIP02 probabilistic projections with the low (SRES B1) and high (SRES A1FI) scenarios

reliability by mid- and end-of-century (by up to 54% and 83%, respectively). Crucially, these projected changes result from both reduced water quantity and quality factors such as suspended solid concentrations or algal blooms.

In addition to the interacting effects of water temperature and nutrient concentrations on water quality and ecological state, there are also potential risks related to saline intrusion/coastal inundation (see also Risk N10: Risks to aquifers and agricultural land from saltwater intrusion). The magnitude of such risks is likely to be heavily dependent on local conditions, such as abstraction, hydraulic gradient, and tidal patterns (Defra, 2014). As an example, at the Bosherton Lakes SAC in west Wales, there is a low, but increasing, probability of tidal inundation from the 2050s to 2080s. Such events could greatly deteriorate features of interest on the site, specifically charophyte communities (Holman *et al.*, 2009). Such events are most likely under conditions of rising sea level, and coincident tidal surge and high tides.

#### 3.12.1.2.4 Species abundance and distribution

Aquatic macroinvertebrate communities are expected to be further affected by future climate change, since they are sensitive to water temperature, oxygen concentrations, flows, and sedimentation (Johnson *et al.*, 2009). In lowland rivers, it is suggested that a shift in composition from species typical of high to low flows is “likely” (Johnson *et al.*, 2009). In Wales, inland waters (e.g., lakes and rivers) were assessed as being highly negatively affected by hotter, drier summers (Berry, R. *et al.*, 2019), with implications for such communities. Modelling of future climate impacts on invertebrate communities within the Welsh Llyn Brianne catchment projected that warming of 1°C to 3°C could eliminate ten (mostly rare) taxa; up to 12% of the local species pool (Jones *et al.*, 2013). Using climate projection data from the rivers Thames and Ouse, Johnson *et al.* (2009) also infer “possible” future changes in the composition of submerged plant communities with rising water temperatures, lower flows, and elevated CO<sub>2</sub> concentrations in river water.

Climate change is also one of a number of possible threats to UK recreational fisheries (Winfield, 2016) with cold-water fish such as Arctic charr already showing declines at least partly related to climate change (Winfield, 2010). Conversely, warm-water species, such as the roach, are projected to expand their range across the UK (Elliott *et al.*, 2015). Whilst such range expansions may be considered an opportunity (see also Risk N13), newly arriving species can have a wide range of impacts upon recipient ecosystems. Salmonid species have limited capacity for genetic adaptation of their upper temperature tolerances with warming (Elliott and Elliott 2010), which raises concerns over the persistence of these species. Indeed, Elliott and Elliott (2010) concluded that “*If winter stream temperatures in southern Britain and Ireland continue to increase at their present rate, then they will soon exceed the lethal limit for egg development in [Atlantic salmon] and [brown trout]*”. Climate change impacts upon species such as salmonids are highly relevant to the sport fishing industry (contributing around £113 million per year to the Scottish rural economy, Scottish Government (2019)). In addition to temperature effects, Johnson *et al.* (2009) suggest that lower flows may result in elevated concentrations of contaminants that would affect sex determination and sex ratios in fish populations, and that rising temperatures could alter disease dynamics. However, the magnitude of these effects is currently uncertain.



Johnson *et al.* (2009) suggest that climate change may adversely affect riverine bird populations through changes in phenology i.e., seasonal mismatching between the timing of chick rearing and the timing of peaks in food resources. However, as noted above (Samplonius *et al.*, 2021), we currently lack sufficient evidence of such effects for many freshwater species. Modelling of changes in suitable climate for birds under the future 3°C-rise scenario projected that common scoter, Slavonian grebe, ruff, pintail and marsh warbler have a high likelihood of extinction (Ausden *et al.*, 2015; Hayhow *et al.*, 2017). In addition, an increasing frequency of extreme events (floods and droughts) could impact aquatic birds by destroying nests and altering feeding opportunities (Johnson *et al.*, 2009).

It should be noted that, under the Water Framework Directive, community composition data for some organism groups (e.g., macroinvertebrates, macrophytes, fish) have been used as indicators of ecological state. Looking ahead, though there is some uncertainty regarding our approach to fresh water regulatory monitoring post EU-exit, climate change could alter status assessments of sites by impacting upon these ecological communities.





































#### 3.12.1.2.5 Socioeconomic scenarios

Using academic literature, published reports and expert opinion, the Environment Agency have developed five qualitative socio-economic scenarios (or “story-lines”) for the water environment of England and Wales, up to 2050 (EA, 2017a):

- I. Uncontrolled Demand (UD, governance is directed towards shorter term socioeconomic concerns, consumption reflects an intensified materialistic “desire economy”).
- II. Innovation (INN, governance systems and decision-making focus on longer term sustainability, consumption reflects an intensified materialistic “desire economy”).
- III. Sustainable behaviour (SB, governance systems and decision-making focus on longer term sustainability, consumption patterns are constrained with a focus on well-being and sustainability).
- IV. Local resilience (LR, governance is directed towards shorter term socioeconomic concerns, consumption patterns are constrained with a focus on well-being and sustainability).
- V. Reference (REF, a future based on a policy and governance context similar to today).

































Consideration of nine indicators of significant water management issues, or exposure pressures, under these socio-economic scenarios showed how the uncontrolled demand and local resilience scenarios could lead to negative impacts on the water environment (Table 3.35) and water management challenges (Table 3.36). Innovation and sustainable actions that seek to build long-term resilience and sustainability, while having opposite patterns of consumption, could have positive or no impacts on the water environment or management challenges (Tables 3.5, 3.6). In their project summary for this work, the Environment Agency (2017b) concluded that “*scenarios that are driven by short-term growth and competitiveness could undermine the requirements of current environmental legislation and make the negative impacts of climate change worse. Conversely, scenarios that are characterised by long-term sustainability may offer substantial environmental improvements, though currently desired environmental outcomes may not be fully achieved*” (p1).

**Table 3.35.** Impacts of four socio-economic scenarios on the UK water environment (redrawn from EA, 2017a. Contains Environment Agency information © Environment Agency and database right.). UD = uncontrolled demand; INN = innovation; SB = sustainable behaviour; LR = local resilience (see text for more detail on the scenarios).

Impacts on the water environment	Scenario			
	UD	INN	SB	LR
Loss of sensitive species				
Invasion and spread of non-native species				
Acidification of soils and waters				
Toxic and sub-lethal impacts on fish and macroinvertebrates				
Obstacles to fish passage				
Detrimental impact on aquatic plants				
Dried out wetlands and ephemeral chalk streams				
Reduced water flows, lower flow velocities and reduced depth				
Alteration of natural flow variability				
Intrusion of saltwater into groundwater				



**Table 3.36.** Impacts of four socio-economic scenarios on the UK water management challenges (redrawn from EA, 2017a. Contains Environment Agency information © Environment Agency and database right.). UD = uncontrolled demand; INN = innovation; SB = sustainable behaviour; LR = local resilience (see text for more detail on the scenarios).

Water management challenges	Scenario			
	UD	INN	SB	LR
Eutrophication				
Acid and nitrogen deposition				
Un-ionised ammonia				
Nitrate in drinking water				
Microbiological contamination				
Sediments				
Chemical pollution				
Hydromorphological alterations				
Water quantity				
INNS				

### 3.12.1.3 Lock-in and thresholds (N11)

Lock in risks could come from the use of hard infrastructure for flood management preventing the adaptation of habitats, while barriers within a river could disrupt species movements.

Potential threshold temperatures have been identified for some climate impacts as part of a national climate impacts screening exercise (Jones *et al.*, 2020):

- *Temperature effects on phytoplankton blooms in lakes.* Phytoplankton blooms can impact negatively on water quality, recreation, and biodiversity. Based on the available evidence, the incidence of such blooms is likely to be greater when air temperatures exceed 17°C. At a UK scale, it is estimated that the number of months per year exceeding this temperature threshold will increase from approximately 1 under baseline (2001-2010) conditions to approximately 2 under a +2°C warming scenario, and 3 under a +4°C warming scenario. This represents a marked increase in the risk of blooms with ongoing climate change. Such blooms can have wide ranging economic impacts, including on property values, water

treatment costs, tourism and fisheries revenue. However, the costs of this risk alone for the UK, based on a single UKCP18 model variation, were projected to increase from £173 million at baseline (2001-2010) to £295 million under a 2°C scenario and £481 million under a 4°C scenario. The same study, using 28 model variants/projections from across the two families of ensembles available from UKCP18 data (PPE and CMIP5) on the trajectory towards a 4 °C world under a RCP8.5 concentrations pathway found that the figures were £329 million and £332 million, respectively, for the 2050s, and £420 million and £332 million for the 2080s.

- *Temperature effects on phytoplankton blooms in rivers:* As above, phytoplankton blooms can impact negatively on water quality, recreation, and biodiversity. Available evidence suggests that blooms in rivers are more likely when temperatures exceed 19°C (based upon Bowes *et al.*, 2016). At a UK scale, it is estimated that the number of months per year exceeding this temperature threshold will increase from <1 under baseline conditions to approximately 1 under a +2°C warming scenario, and 2 under a +4°C scenario. Additional thresholds for higher bloom risk have been identified (flows of <30 m<sup>3</sup> s<sup>-1</sup>, >20 h sunshine during previous 5 days, Bowes *et al.*, 2016) and these could be used to refine projections of bloom exceedance. There is currently insufficient evidence to place an economic value on these changes.
- *Temperature effects on fish habitat volume in lakes:* Cold water fish species, of conservation concern, are especially vulnerable to the effects of climate change. Based upon the example of the vendace (the UK's rarest freshwater fish), it is known that rising water temperatures can reduce available habitat, and that this effect is compounded by the effects of decreases in oxygen concentrations. Water temperatures above 18°C are thought to be detrimental to vendace. At a UK scale, it is estimated that the number of months per year exceeding this temperature threshold will increase from approximately one under baseline and +2°C warming scenarios, to approximately three under a +4°C warming scenario. There is currently insufficient evidence to place an economic value on these changes.
- *Temperature effects on zooplankton species composition in lakes:* Zooplankton are important microscopic grazers of algae in freshwater ecosystems and, as such, contribute to maintaining good water quality. They are also an important food resource for freshwater fish species, especially in their vulnerable young life-history stages. The composition of zooplankton communities will affect these contributions to ecosystem functioning and is sensitive to rising water temperatures, both directly and indirectly, through the impact of warming on algal growth and rates of predation. There is evidence to suggest that, above water temperatures above 14°C, community composition can change. At a UK scale, it is estimated that the number of months per year exceeding this temperature threshold will increase from approximately 3 under baseline conditions to approximately 4 under a +2°C warming scenario, and 5 under a +4°C warming scenario. There is currently insufficient evidence to place an economic value on these changes.

In addition to these examples, critical temperature thresholds have been determined for salmonid fish species which are important to commercial and sports fisheries; the Atlantic salmon, brown trout and Arctic charr (Elliott and Elliott, 2010). These thresholds vary not only among species, but also among life stages for any given species. There is, therefore, the potential for future work to screen for threshold exceedances at multiple life-history stages. However, it is important to note that there is a degree of uncertainty associated with any estimates of threshold exceedance. An

important source of such uncertainty is the fact that climate change interacts with other environmental pressures in affecting freshwater ecosystems. In the case of algal blooms, changes in nutrient loading from catchments and water treatment works, along with changes in water colour (due to organic matter content), and rates of water flow will also have very strong effects on bloom incidence and magnitude. Water bodies with high nutrient loadings, and slow-flowing rivers will be at particular risk of algal blooms. These nutrient effects on algal growth will have cascading effects on zooplankton that are already affected by temperature. Furthermore, nutrient pollution of water bodies will also affect oxygen concentrations by stimulating algal growth, placing additional constraints on cold-water fish habitat. It is likely, therefore, that climate thresholds will be dependent on other environmental factors. Further resolution of the nature of such interactions is a priority for future research.

#### 3.12.1.4 Cross-cutting risks and interdependencies? (N11)

Abstraction of water exacerbates drought effects by reducing water to support ecosystems. Following drought there may be increased concentration of fertilisers, pesticides and other chemicals. All of these factors are likely to affect water temperatures as well (Poole and Berman, 2001; Hannah and Garner, 2015), compounding the effects of climate change. Canalisation of watercourses increases flow rate and reduces water-holding capacity of catchments. Similarly, drainage of wetlands has reduced water-holding capacity.

#### 3.12.1.5 Implications of Net Zero (N11)

Inland waters are an integral part of the global carbon cycle. Lake sediments can act as a long-term carbon sink, and it has been estimated that 820 Pg of organic carbon is buried within such sediments globally (Tranvik *et al.*, 2009). As such, carbon sequestration in lakes may be considered a nature-based solution to contribute to Net Zero targets. However, carbon burial and processing within fresh waters will be affected by ecosystem state, and pressures acting upon it. There is an urgent need to understand these dependencies within the UK and the global context. If done effectively, Net Zero could decrease the magnitude of this risk through agricultural practices that optimise the efficient use of nitrogen on cropland and grassland, leading to improved water quality (see Risks N4 and N6). Afforestation and peatland restoration (see Risk N1 and N5) could also contribute to improving freshwater quality, as well as the reduction of flooding. While beyond the Net Zero Further Ambition scenario, the better use of lowland agricultural peatland (e.g., seasonal management of the water table) could have similar effects.

Freshwater habitats are increasingly hosting floating solar PV arrays across the world, to provide renewable energy and contribute to Net Zero (e.g., the array at Godley Reservoir, Greater Manchester). However, the unintended ecosystem effects, both beneficial and detrimental, of such installations are not well-understood (Armstrong *et al.*, 2020). Such fundamental research is therefore high priority.

## 3.12.1.6 Inequalities (N11)

No inequalities associated with climate change were identified in relation to risks to freshwater species and habitats.

## 3.12.1.7 Magnitude Scores (N11)

**Table 3.37** Magnitude scores for risks to freshwater species and habitats from changing climatic conditions and extreme events, including higher water temperatures, flooding, water scarcity and phenological shifts

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
<b>Northern Ireland</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)
<b>Scotland</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
<b>Wales</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)

Notes: Magnitude categories based on the level of agreement of the evidence and expert judgement of authors (in agreement with CCRA reviewers) are medium for the present day and for future for the 2050s and for the 2080s, on a to pathway stabilising at 2°C by 2100. This means there are intermediate impacts on or loss of species groups across all four UK countries in the 2050s. However, the countries are scored as high risk for the 2080s under a trajectory of a 4°C world at the end of the century, resulting in potential major impacts on or loss of species groups.

## 3.12.2 Extent to which current adaptation will manage the risk (N11)

Research has explored how certain adaptation actions could help reduce the risk of climate change and has helped to inform adaptation. Some examples are given below.

### 3.12.2.1. Thermal refugia (N11)

The provision and preservation of thermal refugia could promote temperature heterogeneity in rivers, and thus aid the survival of cool-water species, such as salmonids, under warming conditions (Kurylyk *et al.*, 2015). For example, deep pools would allow access to deeper, cooler water under drought conditions, and the removal of obstacles could allow salmonids to access cooler inflow streams to lakes (Elliott and Elliott, 2010). Management of clear felling, ground water pumping and aggregate extraction are all options for preserving cool water refuges created by ground water inputs, and planting/preservation of riparian vegetation can shade and cool river reaches. CCRA2 noted that, in order to address the risks to freshwater species from higher water temperatures, more research is needed to refine further the strategic approach to riparian tree planting to provide cooling for sensitive water bodies with high biodiversity. New modelling (e.g., Garner *et al.*, 2017; Jackson *et al.*, 2018) and literature review (Feld *et al.*, 2018) has shown the potential for riparian woodland to decrease mean water temperatures, while forest harvesting could increase them (Millar *et al.*, 2012). Field experiments and modelling in the River Dove, Derbyshire showed that approximately 1 km of riparian shade is needed, at downstream sites, to cool rivers by 1°C in summer (Johnson and Wilby 2015). However, the shading effects of riparian vegetation are contingent on channel width, as well as the width, length and vegetative structure and composition of the riparian zone (Feld *et al.*, 2018); key considerations for mitigation of the effects of climate change via these means. In addition, monitoring of temperatures within existing thermal refugia would provide the evidence needed to preserve and enhance them (Kurylyk *et al.*, 2015).

### 3.12.2.2 Management of water quality (N11)

The impact of warming on algal blooms is synergistic with the effects of the primary stressor, nutrient loading (Rigosi *et al.*, 2014; Richardson *et al.*, 2018), which has a dominant effect on the maximum capacity of algal standing crop in lakes (Carvalho *et al.*, 2013). Therefore, adaptation that primarily focuses on nutrient management will likely reduce the size of the effect that temperature can have on algal biomass.

Nutrients could be reduced through enhanced wastewater treatment processes, which form part of various environmental programmes, such as the National Environment Programme. It is also important to reduce nutrient run-off from agriculture, for example through precision fertiliser application, or by creating buffer strips around fields and water bodies to reduce nutrient loads reaching the water. Capacity is largely available for the application of some land management techniques, which would have immediate benefits, but action depends on the incentives or regulation in place (Jones *et al.*, 2020). Rules within existing agri-environment schemes are targeted at reducing the instances of nutrient run off. In addition, there are relevant policy instruments (see below).

Additional measures, such as in-lake interventions to minimise bloom risk (e.g., chemical remediation, manipulating flushing rates, mixing and aeration, biomanipulation, and shading water columns with floating solar panels), are not widely practiced at present. Therefore, Jones *et al.* (2020) considered the impact of current levels of adaptation on mitigating risks to be low.

In summary, the implementation and improvement of nutrient management practices, to reduce nutrient loading to watercourses, will have immediate benefits. It is likely, however, that further adaptation through land use change (buffer strips, afforestation etc.) may be required to maximise these benefits. Combining these land management changes with water management practices (e.g., chemical nutrient management, mixing and aeration) may allow us to delay exceedance of water quality thresholds. Early action will reduce the risk of lock-in; therefore, timely action is important.

#### 3.12.2.3 Management for sensitive freshwater fish (N11)

Current adaptation measures focusing on catchment-wide management of nitrogen, phosphorus, or reduction in internal nutrient cycling, could be of benefit to rare species, through a reduction in eutrophication and corresponding oxygen depletion. Such measures could also lessen suspended sediment loading to water bodies, and thus siltation of important spawning grounds. As above, these measures would need to be applied more widely to have a significant impact (Jones *et al.*, 2020). Provision of artificial spawning substrates may also help offset the siltation of spawning grounds, and the translocation of eggs and larvae can be used to establish refuge populations in high-quality sites. To our knowledge, these approaches are also not widely applied. Therefore, the impact of current levels of adaptation is thought to be low.

#### 3.12.2.4 Effects of current adaptation policy and commitments on current and future risk (N11)

At the UK level, there is uncertainty about water regulations post-EU-exit and the fate of River Basin Management Plans (RBMPs) post-EU-exit is not clear at the time of writing. The form of EU-exit will affect whether the WFD still applies to the UK, although post-EU-exit, the Scottish government is committed to maintaining water-related regulations. In Northern Ireland, the WFD requires the Republic of Ireland to establish appropriate coordination of transboundary river basins. Defra's 25YEP's targets on water quality could help ensure the good ecological status of water if they are met.

##### 3.12.2.4.1 England

##### 3.12.2.4.1.1 Management of water quality

Water Resource and RBMPs, and WFD actions, are all contributing to reducing other sources of harm in freshwater ecosystems and therefore improving their resilience. The WFD has been important in the environmental regulation of water, ensuring the reporting of the status of fresh water, the setting up of river basin districts and production of RBMPs. The RBMPs are important in formulating adaptation plans for freshwater habitats in England and they consider the impact of reduced water availability as a result of climate change, contain clear outcomes and align to the goals for freshwater habitats outlined in the 25YEP (CCC, 2019b). The Environment Agency is considering what adaptation is needed to 2°C and 4°C degree global temperature scenarios as part of its revisions to the RBMPs, to be published in 2021. The Plans outline required actions to bring freshwater habitats to good ecological status by 2021 or, where this is not possible, by 2027. The Water Industry National Environment Programme is a database of actions for water companies in England, requested by the Environment Agency, which will need to be completed to meet their

environmental obligations. It includes initiatives to tackle sewage discharge (CCC, 2019b), with a view to reducing eutrophication risk and improving water quality. Furthermore, the Environment Agency and Natural England together administer the Water Environment Grant Scheme to improve the water environment.

The Reduction and Prevention of Agricultural Diffuse Pollution Regulations (<https://www.legislation.gov.uk/uksi/2018/151/contents/made>), which include provisions for managing runoff from agriculture, came into force in England in 2018. Current catchment-wide adaptation measures are applied locally, for example in nitrate vulnerable zones, but not widely elsewhere.

#### 3.12.2.4.1.2 Management of water quantity

The Water Industry National Environment Programme is aiming to update ten abstraction licensing strategies by 2021 and all remaining strategies by 2027 to capture agreed solutions to environmental pressures in catchments. These could include solutions to flow issues related to climate change. However, the CCC stated in its last progress report that 'It is not clear how the programme considers the potential impacts of future climate change on freshwater habitats' (CCC, 2019b).

Several of the 25YEP indicators are concerned with water quality and could contribute to measuring adaptation. These include indicators on the state of the water environment and water quality, and water bodies achieving sustainable abstraction criteria. River flows and groundwater levels are sustainable when they support ecology that is only slightly impacted by human activity. Natural functions of water and wetland ecosystems will track changes in the naturalness of ecosystems functioning at the catchment scale, including restoring natural functions contributing to enhancing ecosystem services, such as biodiversity, water purification, flow regulation and resilience to climate change and the health of freshwaters assessed through fish stocks.

Some of the public goods identified as being eligible for financial assistance under the new Environmental Land Management Scheme (e.g., clean and plentiful water) may also contribute to adaptation, as could natural flood management schemes, which are encouraged and supported in National Flood and Coastal Erosion Risk Management (FCERM) Strategies in England and Wales.

Indirectly, natural flood management (e.g., Working with Natural Processes Evidence Directory, EA, 2018b) as a means of addressing flood risks could lead to multiple benefits for freshwater habitats and species, which could reduce the impacts of climate change and assist their adaptation.

#### 3.12.2.4.1.3 Thermal refugia

The 'Keeping Rivers Cool' project in England and Wales (2012-2016), led by the Environment Agency, involved measures to address the risks of warming waters in rivers. For example, it has produced guidance for developing riparian shade for species at risk, with the trees planted also contributing to mitigation (Woodland Trust, 2016). Maps based on this initiative are still being updated and there

remains a need to account for the impacts of water temperature (and reductions in water level) in monitoring and reporting on the ecological state of UK freshwaters.

#### 3.12.2.4.2 Northern Ireland

The Northern Ireland Climate Change Adaptation Programme 2019-2024 (DAERA, 2019a) states that River Basin Management Planning, to meet the targets of the Water Framework Directive, takes account of findings from the latest Climate Change Risk Assessment. Programmes of measures within these Plans are intended to address potential climate change impacts on the Northern Ireland water environment. Furthermore, the Programme promises to identify future areas for riparian planting. WFD reporting in Northern Ireland (NI) yields important data on chemical and ecological status variables that might mediate climate change impacts (DAERA, 2018a). In 2018, 31.3% of NI river water bodies were classified as 'good' status or better. In 2018, nitrate concentrations were monitored at 54 groundwater sites across NI giving an average concentration of 6.14 mg NO<sub>3</sub>/l. At 51 of the 54 groundwater monitoring stations (94%) in 2018, groundwater nitrate concentrations were consistently below 25 mg NO<sub>3</sub>/l. The Groundwater Daughter Directive (2006/118/EC) sets the groundwater quality standard at 50 mg NO<sub>3</sub>/l.

From Northern Ireland's 450 river catchments, there is a desire to see 60 - 80 catchments targeted with the necessary equipment to monitor water quality on an hourly basis, similar to the work undertaken by Teagasc as part of their Agricultural Catchments Programme (DAERA, 2018b).

#### 3.12.2.4.3 Scotland

The Scottish Government (2019) have published their second climate change adaptation programme (Climate Ready Scotland 2019-2024), which includes measures and policies that are relevant to fresh waters:

- A view that the beaver (protected by European law since May 2019) should be allowed to expand its range naturally, since their role as 'ecosystem engineers' could contribute assist ecosystem adaptation to climate change, via wetland habitat creation, and enhancing both habitat and biodiversity. They can also alleviate flooding, improve water quality and bring socio-economic benefits. A Management Framework for Beavers in Scotland has been published on the NatureScot website. There has also been incorporation of 'climate change thinking' into RBMPs, and associated measures to act on flood risk, drought, and impacted ecosystem services. There are two RBMPs: one covering the Scotland River Basin District; and the other cross border for the Solway Tweed River Basin District. There are recognitions that climate change will increasingly affect the magnitude and sustainability of water demand, land use and non-native species spread. Over the period to 2027, work will be undertaken to improve understanding of climate change impacts, and improvement measures will be considered through the lens of preparing Scotland for a future climate.
- Funding and support for projects that work with natural processes to manage flood risk, ecosystem status, and ecosystem services. An example is the Eddleston Water Project (<https://tweedforum.org/our-work/projects/the-eddlestone-water-project/>), managed by the Tweed Forum, monitoring the impacts of wetlands, woodlands, ponds and leaky barriers on



flood risk. The overarching goal of the project is to assess the benefits of working with natural catchment processes to help manage flood risk and river status.

- Creation of a Water Environment Fund, to ease pressures on imperilled species, such as the Atlantic salmon (Scottish Government, 2020a). Salmonids are of great importance to the sport fishing industry (contributing around £113 million per year to the Scottish rural economy).

Managing the quality of runoff from agriculture is regulated led by both the Water Environment (Diffuse Pollution) Regulations and Water Environment (Controlled Activities) Regulations in Scotland in 2008 and 2011, respectively.

#### 3.12.2.4.4 Wales

Wales' latest adaptation plan, "Prosperity for All: A Climate Conscious Wales" (Welsh Government, 2019b), includes actions to maintain, enhance and restore floodplains and hydrogeological systems, to reduce flood risk and improve water quality and quantity. The plan includes sub-actions that will utilise the evidence base and collaborations being developed through Area Statements to deliver targeted interventions in catchments. The adaptation plan also promotes good environmental, agricultural practice to increase the resilience of soils and water, which includes good soils and nutrient management plans.

Under Wales' Natural Resources Policy, Natural Resources Wales has developed seven Area Statements which outline the key challenges being faced by each locality, and how authorities can better manage natural resources for the benefit of future generations. The importance of resilient water quality and quantity is important in all such Area Statements. 'Working with Water' is a key theme for the South Central Wales Area Statement<sup>27</sup> and it aims to support climate change mitigation and adaptation. Similarly, a key theme to the North East Wales Area Statement (<https://naturalresources.wales/about-us/area-statements/north-east-wales-area-statement/?lang=en>) is 'Protecting water and soil through farming and sustainable land management'. It highlights the secondary benefits of sustainable farming to water, for example by providing cleaner water for biodiversity enhancement and to develop resilient ecological networks. The River Clwyd and River Dee catchments are of particular interest in this Area Statement, with concerns for water quality worsened by climate impacts. The Area Statement therefore seeks to promote nutrient reduction, create environmental benefits and nurture successful relationships between stakeholders and communities.

Also, under Wales's Natural Resources Policy, the Second State of Natural Resources Report (SoNaRR2), the register of key pressures and opportunities for freshwater (Natural Resources Wales, 2020b) identifies a number of opportunities for action including protecting and restoring freshwater ecosystems, restoring floodplain connectivity and floodplain wetland habitats at a landscape scale, significantly increasing the number and quality of lowland ponds and develop integrated river-floodplain management plans that integrate land use planning, biodiversity and flood management.

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<sup>27</sup> <https://naturalresources.wales/about-us/area-statements/south-central-wales-area-statement/?lang=en>

SoNaRR2 (Natural Resources Wales, 2020b) views the planting of riparian corridors to help offset future temperature rises and control soil/nutrient loss in storm events as contributing to the aim of resilient freshwater ecosystems. The 'Keeping Rivers' Cool' project mentioned above applies to Wales as well as England.

As with England, Water Resources Management Plans and RBMPs are already contributing to the reduction of harm to freshwater resilience. Welsh Water's Water Resources Management Plan (Welsh Water, 2019) considers how climate change, including drought, will impact both water quantity and quality. Usage efficiency is seen as a way of lowering environmental impacts, while for water quality a catchment management approach is being adopted to manage drinking water, which will involve maintaining or improving the state of freshwater ecosystems. Making Time for Nature (Welsh Water, 2020) sets out Welsh Water's Plans for maintain and enhancing biodiversity. It contains a number of commitments, such as the better management of pesticides, contaminants and wastewater that will help improve water quantity, as well as research into why inland water bodies are failing to achieve good ecological status and the impacts of climate change.

The Welsh Water 2050 vision (Welsh Water, 2018) also seeks to promote biodiversity and ecosystem resilience, for example through managing wastewater to ensure water achieves good environmental status.

#### 3.12.2.5 Effects of non-Government adaptation (N11)

Water companies as part of a green recovery from COVID-19 are being encouraged by the government to consider greater use of nature-based solutions and to look for innovative ideas for the future that could include: water resources, flood mitigation, Net Zero or water quality improvements (Pow et al., 2020). Furthermore, water companies are due to publish Drainage and Wastewater Management Plans (DWMPs) in 2022, in order to address issues of water quality and higher flows (Atkins, 2019).

#### 3.12.2.6 Barriers preventing adaptation (N11)

There is poor evidence available about the barriers to adaptation for freshwater species and habitats. Uncertainty around EU-exit and future water regulations may be a short-term constraint. The financing of RBMPs and other initiatives for the improvement of water quality is a possible ongoing constraint, as is the enhanced monitoring for water quality, but further research is needed in this area.

#### 3.12.2.7 Adaptation shortfall (N11)

While there have been developments in strategy across all the UK's administrations to address risks to freshwater habitats and species, the focus is primarily on the impact of reduced water availability and there is less evidence of adaptation actions to address risks from high water temperatures, as well as the impacts that any actions are having and how these actions will fit within the UK-wide successors to the Water Framework Directive and RBMPs. Current actions, therefore, are thought to be insufficient to manage the future levels of risks down to low magnitude levels by the end of the

century with climate change, though confidence in this assessment is considered low due to the lack of evidence available.

### 3.12.2.8 Adaptation Scores (N11)

**Table 3.38** Adaptation scores for risks to freshwater species and habitats from changing climatic conditions and extreme events, including higher water temperatures, flooding, water scarcity and phenological shifts

Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

### 3.12.3 Benefits of further adaptation action in the next five years (N11)

A clear mechanism that accounts for the consequences of higher water temperature and drying up of water bodies in meeting the WFD targets (and whatever their successors will be across the UK) is still needed. In England, it has been suggested that there needs to be consideration of the 'right' enabling environment (regulatory framework) that would be required to ensure a well-adapted water sector (CCC, 2019c). New environmental land management schemes in the UK post-EU-exit are likely to include measures to reduce diffuse nutrient pollution. However, such adaptation options need to be clearly built into design and piloting.

The effectiveness of a range of sustainable measures to increase ecological resilience through enhancing riparian habitat, providing a more heterogeneous channel bed morphology or creating a range of refugia for freshwater organisms during low flows has been modelled (EA, 2016). The results can point to future possible adaptation measures. It was found that assisted natural recovery was successful in restoring hydromorphological processes, thus enhancing ecological resilience, and could be effective in wandering rivers (which alternate between single-channel and braided reaches). Weir removal could have a similar effect on processes and help in restoring longitudinal connectivity. This could also be achieved through reconnecting channels in active river systems. However, flood embankment removal in wandering rivers did not increase habitat provision under low flow conditions and re-meandering and increasing channel length within low energy systems is unlikely to increase ecological resilience under low flows, but is likely to be more effective in active channels. Natural recovery also was modelled as providing greater habitat quantity and quality than the control reach for brown trout in the River Wharfe, refugia might also be increased, but habitat quality could be slightly lower (EA, 2016). It has also been suggested that small, upstream waterbodies should be especially targeted for management, given their connectivity to the wider catchment, and therefore the potential for downstream effects of stressors acting in these ecosystems (Riley *et al.*, 2018).

### 3.12.3.1 Indicative costs and benefits of additional adaptation (N11)

There is information in general on the costs and benefits of RBMPs for England's water environment, as published in the Impact Assessment (Defra, 2015), which include the options discussed in the section above, i.e., on possible options that might have high relevance for addressing increasing climate related risks. There is also some information published by the EA (2019d) as part of consultation, which highlights the need for an adaptive management approach to enhance the resilience of RBM plans. Similar information covering other parts of the UK has not been identified as yet.

### 3.12.3.2 Overall urgency scores (N11)

**Table 3.39** Urgency scores for risks to freshwater species and habitats from changing climatic conditions and extreme events, including higher water temperatures, flooding, water scarcity and phenological shifts.

Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	More action needed	More action needed	More action needed
Confidence	Medium	Medium	Medium	Medium

There is incomplete knowledge of climate impacts on freshwater habitats and species at present, as well as a current shortfall in adaptation measures created by a lack of evidence for specific actions to help in managing water temperatures in particular and their effects on risk reduction. The risk has therefore been scored as 'More action needed' across the UK, with further investigation also required on the scale of risk and effectiveness of these measures.

### 3.12.4 Looking ahead (N11)

A review of climate change impacts on the water environment in England (Defra, 2014) concluded that our understanding of the interactions between climate change and other stressors is currently incomplete, causing uncertainty in projected outcomes. Although this is an England-specific review, our view is that it also applies across the UK. To address this knowledge gap, there is a need to prioritise research on the responses of freshwater habitats and species to climate change in conjunction with other pressures and to highlight the implications for meeting water management objectives. In addition, there is a need to develop policy-relevant indicators of climate change impacts on freshwaters and to continue investment in the UK's long-term research capability, which enables us to detect ongoing and emerging impacts with reference to baseline/historic variation. This will allow us to better constrain environmental models that are capable of projecting future change.

### 3.13. Risks to freshwater species and habitats from pests, pathogens and invasive species (N12)

- Climate change is likely to affect pests, pathogens and INNS through changed thermal regimes, with impacts on the distribution and spread of various diseases and INNS, the rate at which invaders competitively displace native species, or through increased competition for food.
- The current and future risk is assessed as medium for Northern Ireland, Scotland and Wales, and high for England, due to the greater likely increase in the number of pests, pathogens and INNS.
- The likelihood of increased arrivals of pests, pathogens and INNS to the UK in the future, and the potential role of climate change in facilitating their establishment and spread, means more action is needed, particularly to improve capacity for rapid detection.

#### Introduction

No specific risks to freshwater species and habitats from pests and pathogens were identified in this assessment and there are currently no notifiable freshwater plant pests and diseases in the UK (UK Plant Health Information Portal<sup>28</sup>). However, should this change, pests and pathogens could reduce the health of individual species and their habitats, thus affecting key ecosystem functions. CCRA2 did identify that invasive non-native species (INNS) could be an additional stress on freshwater ecosystems, but currently INNS are primarily a consequence of inadvertent or deliberate introductions, exacerbated by the connectivity provided by rivers and streams. Their impacts include: competition with native species, predation, introduction of disease, harmless airborne pathogens becoming more virulent as the result of hybridising with formerly benign native microbes, hybridisation with native species, habitat alteration, which can lead to increased river flooding and economic costs e.g. from dealing with choked waterways (Kernan, 2015; Hayhow *et al.*, 2019). Whilst there is evidence that the number of freshwater INNS is increasing slightly (e.g., SNH 2017; JNCC, 2019) and the recent warmer winters across the UK have been favourable for the survival and development of many species (see also Risk N2), there is very little evidence on the role of climate change in affecting the rate of establishment of aquatic invertebrates (Hulme, 2016).

Currently, most of the INNS are arriving from the continent as a result of anthropogenic factors and their distribution is expanding. There is less information on pests and pathogens, but some of the INNS also carry pathogens. The current and future risk for England is assessed as high, due to the greater likely increase in the number of pests, pathogens and INNS and expansion of their range. The current and future risk is assessed as medium for Northern Ireland, Scotland and Wales, as there are a number of impacts on native species and communities. There is a range of adaptation policies and actions in place, but the likelihood of increased arrivals of pests, pathogens and INNS, and the potential role of climate change in facilitating the establishment and spread of some and the benefit of rapid detection and action, means that more action is needed.

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<sup>28</sup> <https://planthealthportal.defra.gov.uk/>

### 3.13.1 Current and future level of risk (N12)

Note: currently available evidence is not sufficient to allow us to report on the current and future level of risk for each UK country separately.

#### 3.13.1.1 Current risk (N12)

Over 130 INNS are present in freshwater in the UK, with many of them being first reported in the Thames region (Jackson and Grey, 2013; Gallardo and Aldridge, 2020). In Scotland, about two thirds of the invasive non-native species (INNS) are higher plants (i.e., excluding mosses, liverworts, fungi and diatoms) and about 13% are found in inland surface water, whilst 26% of the top 50 INNS affect freshwater (SNH, 2017). About 35% of all notified freshwater habitat features in Scotland have INNS as a pressure, which is increasing; many of these are in an unfavourable overall condition, making them more susceptible to invasion (ClimateXChange, 2018). While in Northern Ireland, seven out of the 11 widespread INNS are associated primarily with freshwater or wetland habitats.

Various modelling studies on the impacts of climate variables on the potential distribution of selected INNS showed that mean annual temperature (Kelly *et al.*, 2014) and minimum temperature of coldest month (Gallardo and Aldridge, 2013a; Kelly *et al.*, 2014; Gallardo and Aldridge, 2015) were the most important variables. Cold temperatures can prevent or restrict the establishment of warm-water species, whilst warmer temperatures can lead to range expansion and population increases (Kernan, 2015),

Some current INNS in freshwater habitats, for example signal crayfish (*Pacifastacus leniusculus*) in rivers, result from the introduction to the UK for commercial purposes, followed by species' escape or deliberate release, leading to both competition with the native white-clawed crayfish (*Austropotamobius pallipes*) and the transmission of the deadly crayfish plague, caused by the fungus *Aphanomyces astaci*. This, together with competition, has led to the decimation of the native crayfish. Climate change may play a role in the spread of the signal crayfish and increased competition. Firkins (1993) found that the signal crayfish has a temperature tolerance which is between 1.3°C and 3°C greater than that of the white-clawed crayfish, which has an upper temperature tolerance of about 28°C. The red swamp crayfish (*Procambarus clarkii*) also is found in England and is a vector of crayfish plague, which is responsible for much of the disappearance of native crayfish species (Souty-Grosset *et al.*, 2016). It has severe impacts on aquatic ecosystems, due to its rapid life cycle, dispersal capacities, burrowing activities and high population densities, and is considered an invasive.

The Chinese mitten crab (*Eriocheir sinensis*) also has been identified as modifying natural habitats and competing with or outcompeting native species (e.g., the white-clawed crayfish), as well as transmitting crayfish plague. Currently there is little information on the effect of climate on its spread.

There are also other important INNS with already established populations in the UK, for example, the killer shrimp (*Dikerogammarus villosus*) which is considered one of Europe's most damaging INNS (Gallardo *et al.*, 2012; Hayhow *et al.*, 2019). It can cause population declines of many native species, as well as preying on other shrimp species, fish larvae and eggs, thus altering ecosystems. Bioclimate modelling of this species showed that approximately 60% of Great Britain currently has

the minimum climatic suitability for its establishment (Gallardo *et al.*, 2012). This, combined with freshwater connectivity and the presence of zebra mussels (*Dreissena polymorpha*), which facilitate the dispersal of the killer shrimp, mean that it could pose a future risk. Also, the quagga mussel (*Dreissena rostriformis bugensis*) which impacts the depressed river mussel (*Pseudanodonta complanata*) and zebra mussel are highly invasive non-native freshwater mussels from the Ponto-Caspian region. They can significantly alter whole ecosystems by filtering out large quantities of nutrients and are serious biofouling risks blocking pipes, smothering boat hulls and other structures (Atkins Global, 2019; Gallardo and Aldridge, 2020).

A freshwater amphipod (*Gammarus pulex*), which is native to Europe, but invasive in Ireland, has replaced the native amphipod (*Gammarus duebeni celticus*) and negatively impacted native macroinvertebrate communities (Lavery *et al.*, 2017). It is also an intermediate host to the fish parasite (*Echinorhynchus truttae*) which can alter host behaviour to facilitate consumption by its final host brown trout. Laboratory and a microcosm experiments, showed a positive relation for *G. pulex* between temperature and maximum feeding rates. The parasite may also be increasing its feeding rate and thus there is a risk of great infection at higher temperatures (Lavery *et al.*, 2017).

Many invasive aquatic plants reproduce very quickly and outcompete native plants as a result. For example, the water fern (*Azolla filiculoides*) can form dense floating mats covering water surface and obstruct sunlight from entering the water.

Whilst the focus has been on the impact of changing temperature on pests, pathogens and INNS, it is thought that drought may make ecosystems more susceptible to invasion (Kernan, 2015). Studies of the 1976 drought in the UK suggest that the reduction of aquatic habitats led to the extensive movement of water birds, which was likely to have been an important factor in the spread of pathogens, but only one documented example is known – that of the introduction of the trematode (*Tylodelphys podicipina*) to Slapton Ley in Devon (in Morley and Lewis, 2014). The 1976 drought also affected a wide range of pathogens and host–pathogen associations, although they mostly appear to have been relatively short-lived, largely due to the heavy rainfall which broke the drought (e.g., Suppl Table 6, Morley and Lewis, 2014). Morley and Lewis (2020) have recorded the effect of drought conditions (1995-1996) on two eye fluke species from perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*). They found that *Tylodelphys sp.* decreased in prevalence in roach but not perch with the onset of drought conditions, while *Diplostomum sp.* showed a decrease in both species. Thus, climate change driven drought could represent an opportunity (Risk N13). There is no evidence of the effects of low likelihood high impact events.

Climate does have a role to play in affecting the risk from pests, pathogens and INNS. However, modelling of the possible human influence on the invasion of 126 non-native freshwater birds, crustaceans, fish, molluscs and plants, found that connections with human recreational activities had a stronger effect on invasion than all other environmental (elevation and annual mean temperature) or anthropogenic predictors (e.g., urban land cover, human population density), with the exception of recording effort and also lake presence for non-native birds (Chapman *et al.*, 2020). Thus suggesting the importance of human interactions and activities in the spread of INNS, with temperature being an insignificant factor.

### 3.13.1.2 Future risk (N12)

The future role of climate change on the arrival of INNS, and possibly pests and diseases, may be low. An expert horizon scan of the likelihood of arrival, establishment/spread and impact on biodiversity of INNS found that of the top potentially most important INNS for Great Britain five (out of 30) were freshwater (Roy *et al.*, 2014a). For the island of Ireland 18 of the top 40 were freshwater species, with the signal crayfish in the top place, killer shrimp in third place and the salmon fluke (*Gyrodactylus salaris*), which can cause serious disease in salmon, trout and some other freshwater fish, in fifth place (Lucy *et al.*, 2020). It is also in the top 30 for Great Britain. Natural spread, which could be a consequence of climate change, however, was not identified as a pathway of arrival for any of them, thus indicating that climate change is not a major factor in the arrival of species.

Given increases in the number of non-native species arriving in the UK, especially in England, and the percentage becoming invasive, it is thought that the number of INNS is likely to increase and spread under climate change (Hayhow *et al.*, 2019). This is supported by experiments on management methods for the signal crayfish which found that increasing water temperatures increased the catches in traps across sites (Stebbing *et al.*, 2016). An experiment also has shown how increasing water temperatures can increase the feeding rates of the signal crayfish (Rodríguez Valido *et al.*, 2021). Climate change also is likely to alter the areas from which INNS could come, their range within the UK, the number of species and their composition (in House of Commons Environmental Audit Committee, 2019). Modelling of the 11 most important INNS as identified by water companies in the UK showed that they had the potential to increase by an average 6% and 12% with scenarios of approximately 1.5°C and 5°C global warming<sup>29</sup> respectively (Gallardo and Aldridge, 2020). Water companies at the highest risk of invasion from these species now and in the future included Cambridge Water, Anglian Water, Affinity Water and Thames Water. Northern Ireland Water, Welsh Water, South West Water and Scottish Water are likely to be least affected.

Climate change may also alter competitive relationships. Modelling of the potential suitable climate space of the zebra mussel and the depressed river mussel and signal crayfish and the white-clawed crayfish using two GCMs (CCma-CGCM and HadCM3) and two emissions scenarios (A1b and B2a) for the 2050s suggested that temperature-related variables were the most important predictors of potential future ranges, especially annual temperature and seasonality (Gallardo and Aldridge, 2013a). A combination of the four climate scenarios showed that the overlap between the two pairs of species is likely to be maintained or possibly slightly increase in the UK.

However, climate is not the only factor affecting species movements. Modelling for Great Britain and Ireland of the invasion potential of 12 aquatic INNS, using nine environmental and four socio-economic factors, found that minimum (air) temperature was the most important factor, followed by distance to ports (Gallardo and Aldridge, 2013b). The latter was particularly important for the quagga mussel, red swamp crayfish (*Procambarus clarkia*) and bloody red mysid (*Hemimysis anomala*). Suitability for the 12 species was highest in England, followed by Wales, then Ireland and lastly Scotland. South-east England was particularly suitable due to environmental factors, but also its proximity to the continent and port activity. The inclusion of the socio-economic factors led to a 6.5 fold increase in the area predicted suitable for the quagga mussel. Similarly, an analysis of the

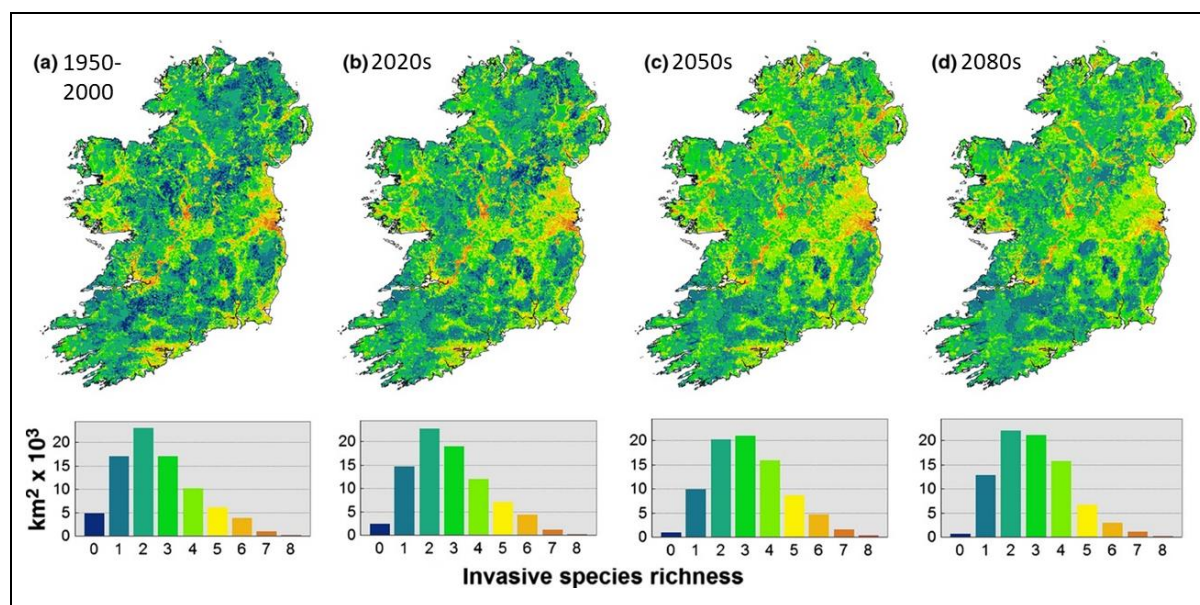
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<sup>29</sup> CCSM4 climate model driven with the RCP2.6 and RCP8.5 concentrations pathways



potential risks to Great Britain from 23 freshwater invaders from the Ponto-Caspian region (south-east Europe), showed that while environmental variables can explain about 60% of the distribution, the human influence index could explain a further 25% (Gallardo and Aldridge, 2015). South-east England showed the highest suitability for these species, with a band along the southern Welsh coast and around some estuaries on the Scottish east coast. Negative interactions were thought primarily to occur through predation of native species.

For Ireland, modelling of the impact of climate on 15 INNS (eight currently established, seven potentially high-risk species, which are either not currently present in Ireland or present at fewer than five sites), showed mixed species responses to projected future climate change (Kelly *et al.*, 2014; Figure 3.16). Under a scenario of approximately 4°C global warming at the end of the century, the potential suitable climate space was projected increase moderately for three species already well established in Ireland (*A. filiculoides*, *L. minuta* and *M. aquaticum*) and increase significantly for three species only occurring at one or two sites (*E. densa*, *H. verticillata* and *L. grandiflora*). While two well-established species (*E. canadensis* and *E. nuttallii*) were projected to decrease and three to show little change. However, in regional environmental niche models for Ireland, incorporating additional non-climate factors (e.g., human influence, land use and soil characteristics), land use and nutrient concentration variables had the greatest overall importance, although for water fern (*Azolla filiculoides*), climate was more important. This species is likely to benefit from increased water temperatures, whilst projected increased flooding also may promote its spread within catchments by dispersing vegetative or seed inoculum (Millane and Caffrey, 2014).



**Figure 3.16** Temporal changes in 'hot- and coldspots' of invasions in Ireland. Maps show the numbers of invasive species, shown by colours as defined in the histograms below, for (a) baseline conditions using 1950-2000 observed data, and projected climates for the (b) 2020s, (c) 2050s, and (d) 2080s, for a scenario of approximately 4°C global warming at the end of the century<sup>30</sup>. Histograms show the distributions of invasive species richness. Reproduced from Kelly *et al.* (2014).

<sup>30</sup> CSIRO MK2 climate model driven by the SRES A2 scenario

Future projections based on regional models under a high emissions scenario suggest currently unsuitable locations increasingly will become suitable and hotspots of invasion suitability will be around major cities and river systems.

It is also possible that non-native species in the UK and currently not invasive could become so. For example, the non-native pumpkinseed fish (*Lepomis gibbosus*) is currently found only in ponds south of the Thames basin and currently it is not considered invasive as populations have been slow growing. However, it is thought that with climate change, it could become invasive, as greater flooding could increase its dispersal from ponds into rivers (Fobert *et al.*, 2013). It also likely to lead to increased recruitment and survival rates, with consequent stronger competitive effects on native species for food resources.

Climate change is also one of a number of possible threats to UK recreational fisheries (Winfield, 2016), with fish, such as Arctic charr already showing declines at least partly related to climate change (Winfield, 2010).

#### 3.13.1.3 Lock-in and thresholds (N12)

Pest, pathogens and INNS are more difficult and costly to manage once they are established and therefore good biosecurity practices and monitoring is needed to enable their detection, so effective treatment can be undertaken.

The arrival of pest, pathogens and INNS is often associated with particular events, be it the arrival of a transport vehicle/vessel or favourable climatic conditions. All species have thermal tolerances, but many of these are not documented in the literature or are unknown. With the signal crayfish having a higher temperature tolerance than that of the native white-clawed crayfish, once the former has been introduced, climate change can lead to the expansion of population numbers, with potential competitive consequences for native species. At a very local scale, spread can be associated with flooding.

#### 3.13.1.4 Cross-cutting risks and interdependencies (N12)

Pests, pathogens and INNS will interact with several other risks. The interacting risks project (WSP *et al.*, 2020) identified that increased drought stress (in winter or summer) could cause changes to pest and disease distributions, which could require greater pesticide use, with impacts on waterways, water quality and freshwater species (Risk N11). For INNS, warmer seasons may make freshwater more habitable for invasive species (WSP *et al.*, 2020), which again could lead to increased pesticide usage. INNS are also likely to compete with native species (Risk N11). Plant INNS can affect the integrity of flood defence structures, impede water flow and exacerbate flooding (Risks I2 and I4), impede navigation or recreational activity and decrease aesthetics and pose problems to health (Gallardo and Aldridge, 2020).

In Great Britain, direct management costs for freshwater INNS have been estimated at £26.0 million per year (Oreska and Aldridge 2011), of which at least £4.6 million are borne by the water industry (Williams *et al.*, 2010). As these figures are only direct costs, and do not include direct damage to infrastructures and service losses resulting from infestations they are likely to be conservative. Those for Northern Ireland have been estimated at over £46.0 million (Kelly, 2014). For the UK, the direct market impacts of signal crayfish on angling have been estimated as £1.0 million and the annual

control costs as £8.8 million, while for zebra mussels, market-based damages and control costs are estimated as £18.7 million (Oreska and Aldridge 2011; Williams *et al.*, 2010). Also, it is expected that climate change will lead to more INNS and to those present expanding their range. Early intervention in an invasion is recommended as there is likely to be an exponential increase in costs of control as an invasion progresses. The economic impacts of algal blooms in lakes and rivers for the UK were estimated to be in the order of £330 million to £420 million, not including other costs, such as clearing clogged waterways, cleaning water and loss of tourism revenue due to impacts on aesthetics (Jones *et al.*, 2020).

Given the importance of humans in the introduction of INNS, then changes in trade patterns or frequency (Chapter 7: Challinor and Benton, 2021) or developments in water infrastructure that enhance connectivity could impact this risk. For example, inter-basin transfers may be an adaptation option considered as part of addressing risks to public water supply from reduced water availability (Risk N18). This could result in the transfer of INNS. In the case of water transfer from the Severn to the Thames Basin, this could lead to the spread of the quagga mussel in the Thames, which could pose a serious threat to the conservation of freshwater mussels in the river (Gallardo and Aldridge, 2018). It is not known how changing trade patterns might affect the magnitude score, but inter-basin transfers could lead to an increase.

#### 3.13.1.5 Implications of Net Zero (N12)

Freshwater pests, pathogens and INNS are unlikely to have much impact on achieving Net Zero, but the restoration or (re-)creation of wetlands could increase habitat availability for a few species.

#### 3.13.1.6 Inequalities (N12)

No inequalities associated with climate change were identified in relation to risks and opportunities freshwater species and habitats from pests, pathogens and INNS.

#### 3.13.1.7 Magnitude scores (N12)

Magnitude categories (Table 3.40) are based on some independent evidence and the expert judgement of authors (in agreement with CCRA reviewers) of high present day and, therefore, likely high magnitude impacts on species groups for England, based on a greater risk from INNS (category: 'Major impacts on or loss of species groups'). Northern Ireland, Scotland and Wales are assessed as medium (category: 'Intermediate impacts on or loss of species groups').

**Table 3.40** Magnitude score for risks to freshwater species and habitats from pests, pathogens and invasive species.

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Northern Ireland</b>	Medium  (High confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)
<b>Scotland</b>	Medium  (high confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)
<b>Wales</b>	Medium  (High confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)

### 3.13.2 Extent to which current adaptation will manage the risk (N12)

Adaptation measures to manage pests, pathogens and INNS in freshwater are not straightforward owing to the different impacts of climate change on these and native or target species (Kernan, 2015) and the important role of other factors in affecting the species' arrival, spread and establishment. Adaptation can include the prevention of the arrival of species, their expansion once arrived and increasing the resistance of habitats to invasion through enhancing their condition. Physical, chemical and/or biological control measures have been successful in the eradication of some freshwater INNS (Hayhow *et al.*, 2019; Horrill *et al.*, 2019), although their invasion often has not been driven by climate change.

While there is successful reduction/eradication of certain INNS, for example, coypu, muskrat, African clawed toad, fathead minnow and black bullhead (Hayhow *et al.*, 2019), others species and habitats still remain a risk and with the arrival of new ones, risks are not likely to have reduced.

### 3.13.2.1 Effects of current adaptation policy and commitments on current and future risk (N12)

In the UK there is a wide range of existing biosecurity policies and commitments for managing the risks from pests, pathogens and INNS, many of which come from EU legislation. Much of the policy framework for adaptation for freshwater pest, pathogens and INNS is the same as that for terrestrial species (see Risk N2). For example, Defra, Scottish Government and Welsh Government (2015a) are working to the Great Britain Invasive Non-native Species Strategy, which covers both terrestrial and freshwater species and Northern Ireland has a similar strategy. This section, therefore, does not repeat that material, but includes any other relevant measures specific to freshwater. It is worth noting that the Great Britain Invasive Non-native Species Strategy work has continued work on eradicating priority invasive freshwater species, (such as topmouth gudgeon, water primrose, variable-leaved watermilfoil, ruddy duck and American bullfrog), as well as managing well established species, such as floating pennywort.

Monitoring is key and is carried out by a number of organisations, including water companies, as early identification and treatment is important. INNS are currently considered by the UK under the EU Water Framework Directive, as part of assessing the ecological status of water bodies, which are downgraded from high or good ecological status if they have INNS present (Boon *et al.*, 2020). This informs the UK guidance for river Special Areas of Conservation, which should have ‘No high-impact alien species established’ (JNCC, 2016). Some INNS actions also form part of current River Basin Management Plans.

Adaptation actions currently are mostly focused around dealing with the current situation, although climate change is recognised as likely to increase the issue of biosecurity. Various initiatives exist or have been set up specifically related to freshwaters.

There are also campaigns, such as Check, Clean, Dry and Be Plant Wise, which have raised the awareness of INNS with key stakeholders, anglers and boat users (GB Non-native species Secretariat, 2019), but not that of the wider public (Creative Research, 2018).

One of the main challenges in terms of managing the impact of invasive species is that, in most cases, freshwaters are impacted by multiple interacting anthropogenic stresses, from eutrophication, climate, physical alteration and atmospheric pollution among others (Kernan, 2015). Thus, addressing some of these other stresses may enhance resistance to invasion. In some cases, in order to protect native species from INNS, it may be necessary to consider moving native species to climatically suitable areas outside of their current range, which either are not suitable for the invading species or cannot be reached by it, either naturally or due to the creation of barriers (Capinha *et al.*, 2013). The creation of isolated sanctuaries or “ark sites” have been accepted for the white-clawed crayfish, which is under threat from introduced crayfish, but additional methods are likely to be necessary.

#### 3.13.2.1.1 England

England is mostly covered by more general UK/British initiatives.

### 3.13.2.1.2 Northern Ireland

Waterways Ireland, a North South Implementation Body, works with other stakeholders and boat owners to control the spread of INNS.

### 3.13.2.1.3 Scotland

In 2018, Scotland set up the four-year Scottish Invasive Species Initiative (SISI) to tackle INNS alongside rivers and water courses in northern Scotland, focusing particularly on Giant hogweed, Japanese knotweed, Himalayan balsam, American skunk cabbage, White butterbur and the American mink.

### 3.13.2.1.4 Wales

The Wales Resilient Ecological Network (WaREN) is devising a new collaborative framework to help public and private bodies and community groups to tackle the significant impacts of INNS, which will focus on 16 INNS, including swamp stonecrop or New Zealand pigmyweed (*Crassula helmsii*). Also, INNS will form a cross-cutting theme in the forthcoming Welsh State of Natural Resources Report ((Natural Resources Wales, 2020b).

### 3.13.2.2 Effects of non-Government adaptation (N12)

Some shortfall might be addressed by non-governmental adaptation, as the Wildlife Trusts and other organisations, stakeholders or the public follow governmental guidance or awareness raising campaigns (e.g., Check, Clean, Dry and Be Plant Wise), but our view is that on its own it is likely to be insufficient to address the adaptation shortfall at the UK-wide level. Also, volunteers increasingly are being used to help with monitoring and control programmes, while the general public are being encouraged to notify sightings of pests, pathogens and INNS.

### 3.13.2.3 Barriers preventing adaptation (N12)

The barriers are the similar those for Risks N2 and include:

- Research and understanding: there has been little monitoring and evaluation of the role of climate change in the risk of INNS.
- Surveillance and inspections: insufficient inspectors at potential entry points and insufficient monitoring may limit the implementation of adaptation actions. In Wales, extending surveillance to cover military and civil facilities is being considered (Welsh Government, 2019c). Also, by restricted international collaboration and access to international pest surveillance data, especially post-EU-exit.
- Funding: this may be linked to both research and to capacity building, with Governments intending to release funds for the latter (e.g., Welsh Government, 2019c; NI Invasive Species Strategy)
- Policies: the UK Government's current definition of INNS does not include species that arrive in the UK as a result of climate change (CCC, 2019b).

- Need for wide stakeholder involvement: addressing the risk requires the involvement of a wide range of stakeholders, encouraging them to mainstream biosecurity surveillance and actions into their work and sometimes cross-border co-operation.

#### 3.13.2.4 Adaptation shortfall (N12)

As is the case for the other risks in this chapter that focus on pests, pathogens and INNS, current adaptation actions to manage risks are primarily focused around dealing with the present-day situation. While some policies do recognise climate change as likely to increase the issue of biosecurity, our view is that there is still a significant adaptation gap in managing projected future risks and additional government intervention is required to bring the risk down to a low level by the 2080s (Table 3.41).

#### 3.13.2.5 Adaptation Scores (N12)

<b>Table 3.41</b> Adaptation scores for risks to freshwater species and habitats from pests, pathogens and invasive species			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

#### 3.13.3 Benefits of further adaptation action in the next five years (N12)

The risks are not likely to decrease in the next five years and, given the environmental and economic benefits of taking early action on eradicating or controlling pests, pathogens and INNS, increasing monitoring and surveillance would be beneficial (CCC, 2019b).

##### 3.13.3.1 Indicative costs and benefits of additional adaptation (N12)

As highlighted by the numbers above, once freshwater INNS become established, damage costs can be high, as can annual control costs. There is therefore an economic case for further uptake of existing adaptation measures to prevent introduction and establishment, rather than attempt to mitigate spread and address impacts. One issue is to know where to focus such efforts: Gallardo and Aldridge (2020) undertook an example to prioritise risks (using cost-effectiveness for the prioritisation) identifying eleven invasive species that are most likely to cause disruption to the abstraction and distribution of water companies in the UK under climate change. There is also general information on the costs and benefits of River Basin Management Plans for England's water environment, as published in the Impact Assessment (Defra, 2015) and these include potential options for preventing the spread of INNS. These include biosecurity measures, monitoring, enforcing legislation banning or restricting the possession, sale and release of certain species, support for further research aimed at developing effective eradication methods and rapid response

for early invasion. These actions are collectively shown to be economically efficient, i.e., benefits outweigh costs.

### 3.13.3.2 Overall Urgency Scores (N12)

**Table 3.42** Urgency scores for risks to freshwater species and habitats from pests, pathogens and invasive species.

Country	England	Northern Ireland	Scotland	Wales
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Medium	Medium	Medium

While a range of adaptation policies and actions are in place across the UK administrations, the likelihood of increased arrivals of pests, pathogens and INNS, combined with the potential role of climate change in facilitating the establishment and spread of some, and the benefit of rapid detection and action, means that more action is needed to meet current and future risk.

### 3.13.4 Looking ahead (N12)

As with terrestrial species (Risk N2) enhanced monitoring, surveillance and early response measures to manage the freshwater risks of pests, pathogens and INNS would be beneficial, with international co-operation important post EU-exit. Cross-sectoral collaboration should improve the effectiveness of adaptation actions. Further research would enhance our understanding of the role of climate change in this risk and any specific adaptation actions required.

## 3.14. Opportunities to freshwater species and habitats from new species colonisations (N13)

- Opportunities to freshwater habitats from new species colonisations can include enhanced biodiversity, which supports a range of ecosystem services, particularly cultural ones such as recreation.
- Opportunities from climate change are assessed as low for the UK and for the DAs, both currently and in the future, as there is low evidence.
- Many of the opportunities for freshwater species and habitats do not come directly from climate change, but from human activities/trade, thus they have a low magnitude score and are assessed as “sustain current action”.



## Introduction

This was not a separate risk in CCRA2 and no specific opportunities to freshwater species and habitats were identified. As with Risk N3, new species are migrating into the UK (Roy *et al.*, 2014a) and, while this is consistent with climate change, especially if they have come from the continent, it is often difficult to attribute this to climate change, with humans frequently implicated in their arrival. Given suitable habitat, it is likely that they will expand their range, although there is potential for a few to become invasive, with negative effects on native species, altering community composition and function, in which case they become a risk covered in Risk N12. Invertebrates are the dominant freshwater non-native species to have arrived in Britain, including 12 non-native crab species (Roy *et al.*, 2014b). Opportunities can also arise from native species expanding their ranges northwards. In both cases, they can enhance species richness and contribute to community adaptation to climate change, but they could also lead to the decline of existing species populations. However, other factors, such as habitat availability and food sources have an important role to play in the realisation of the opportunity posed by climate change.

The opportunities from climate change are assessed as low for the UK and for the DAs, both currently and in the future, as there is low evidence of the opportunities across taxa and climate is likely to play a smaller part in them than other anthropogenic factors. Many of the adaptation actions that are taken to combat the risk to freshwater species (Risk N11) will facilitate species realising any opportunity and thus sustain current action is recommended.

### 3.14.1 Current and future level of opportunity (N13)

Note: it has not been possible to split the evidence of current and future level of opportunity by UK country.

Opportunities for freshwater species may not only enhance biodiversity, but they can also contribute to ecosystem services, especially cultural ones, such as recreational angling and enjoyment of wildlife, with possible associated business opportunities (B7).

#### 3.14.1.1 Current opportunity (N13)

There is relatively little evidence of the opportunities for less mobile taxa, but a number of wetland birds, such as, little egret, red necked grebe, little bittern, have arrived and started breeding (Moss, 2014) and some native wetland birds are increasing in population numbers, although this can vary across countries (Frost *et al.*, 2020). Similarly, the range margins of most southern species of damselflies and dragonflies are moving northwards (Mason *et al.*, 2015). However, these changes cannot necessarily be attributed (solely) to climate change, with a study of macroinvertebrates in the UK (but excluding these odentates) finding that the long-term species recovery in rivers was primarily due to improvements in water quality in northern England (Vaughan and Ormerod, 2012). However, over periods of less than two years, changes in the invertebrate communities could be associated with discharge and temperature. Also, other factors, such as habitat loss and fragmentation and management practices may slow their spread.

Spatial climate–abundance models for north western European (Ireland, UK, France and The Netherlands) seabirds and wintering waterbirds found climate change is likely to have been a significant driver of large-scale population trends in bird assemblages (Johnston *et al.*, 2013). Summer temperature was the most important predictor variable, followed by summer precipitation and winter temperature. They suggested that the positive effect of winter temperature on wintering birds could be a consequence of improved survival, whilst negative effects could be the result of changes in prey populations. Increased temperatures are thought to have had some positive effects on other taxa. For example, for floating plant species and introduced species, it can increase their productivity leading to greater community prominence (Moss, 2014). Eurythermal fish, such as bream (*Abramis brama*), common carp (*Cyprinus carpio*), pike (*Esox lucius*), perch (*Perca fluviatilis*) and/or shad (*Alosa spp.*) appear to be responding positively to warming, as has the introduced roach (*Rutilus rutilus*) in Ireland, whose populations have been supported.

#### 3.14.1.2 Future opportunity (N13)

Future opportunities for freshwater species include arrivals, range expansion and species population increases, however analysis is currently limited. The analysis of the potential risks to Great Britain from 23 freshwater invaders from the Ponto-Caspian region (south-east Europe), showed that 14 species could affect native species more positively than negatively, with most being crustaceans that serve as prey for fish and mussels and provide habitat to other species (Gallardo and Aldridge, 2015). However, as noted in the opportunities for terrestrial species (Risk N3), while environmental variables could explain about 60% of their distribution, the human influence index could explain a further 25%.

Climate change is also likely to lead to more birds arriving and breeding in the UK (Moss, 2014), as well as changes in population numbers. For wintering waterbirds, in a UK scenario approximately consistent with 4°C global warming in the 2080s<sup>31</sup>, while there could be 58% more birds in the entire wintering waterbird assemblage in 2080, the mean population change was projected to reduce by 33% when averaged across species (Johnston *et al.*, 2013). This was due to a few species having very large projected population gains, while most declined.

Water temperature is strongly correlated with spawning success for the twaite shad (*Alosa fallax*). An investigation of populations of this species in the Afon Tywi SAC, Wales, found that annual mean temperature estimates are below the critical threshold of 17.8°C required for spawning, although inter-annual variability results in some success (Knights, 2014). However, using the UKCP09 mean temperatures and increasing them by 1°C, 2°C and 3°C per century led to marked improvements in recruitment success in two river sections and some marginal increase in others. Out of six non-native fish species established in England and Wales, the common carp is predicted to be the most positively affected by 2050 by increases in air and water temperatures (Britton *et al.*, 2010). This, combined with propagule pressure, suggest that it could become invasive with possibly severe consequences for habitat destruction, water turbidity and loss of macrophytes.

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<sup>31</sup> 50<sup>th</sup> percentile of the UKCP09 probabilistic projections with the A1FI emissions scenario in the 2080s (Murphy *et al.*, 2009). The projected changes in annual mean UK temperatures are within the upper end of the range for 4°C global warming in the UKCP18 derived projections (Gohar *et al.*, 2018).

As with terrestrial species (Risk N3), new species colonisations driven primarily by climate change are likely to result in species from Europe arriving in southern England, but increasingly trade, especially with south east Asia, is important in the arrival of non-native species (Roy *et al.*, 2014a). Shifting trade patterns following EU-exit and a development of the Asian market could be particularly relevant. For species already present, but expanding their range or increasing their populations, the realisation of the opportunities will depend on their sensitivity to the climate changes and other driving factors. Thus, there will be geographic variations, but there is not enough evidence to be more specific.

#### 3.14.1.3 Lock-ins and thresholds (N13)

Depending on responses to risks of flooding and to water supply, greater grey infrastructure could increase the barriers for species movements in rivers and channel modification alter habitat availability.

Each species has bioclimatic constraints (e.g., Knights *et al.*, 2014), which, for opportunities for freshwater species, means that they will benefit from warmer air and/or water temperatures. The benefits are likely to increase with the higher emissions scenarios and over time, providing a critical upper threshold is not reached. Similarly, as water levels and flows are important for species, so increases in precipitation could be beneficial, with flooding aiding species spread. However higher discharge rates could be negative for non-mobile species which might be dislodged or affected by bank erosion, whilst prolonged or frequent drought could lead to the extirpation of populations.

#### 3.14.1.4 Cross-cutting risks and inter-dependencies (N13)

The key interaction is with the risk of pests, pathogens and INNS (Risk N12), as if there is a rapid growth of species populations and widespread movement, then the species should be considered an INNS. Similarly, negative effects on the health of native species would mean that the species needed to be controlled or eradicated. Flooding can provide an opportunity for species dispersal into new habitats, although as noted above, adaptation measures to address this may impact negatively on freshwater species.

Use of natural flood management (or working with natural processes) is a nature-based solution and increasingly is used as a part of overall flood risk management plans, especially to manage small peak flows (EA, 2018b). It may involve the restoration of habitats, including woodland, peatland and moorland, as well as coastal ecosystems. This could enhance habitat availability for certain species, while the effects of natural barriers in rivers compared to hard structures is unknown, it is likely that they are permeable to small organisms.

#### 3.14.1.5 Implications of Net Zero (N13)

There are unlikely to be any implications for Net Zero.

#### 3.14.1.6 Inequalities (N13)

No inequalities associated with climate change were identified in relation to opportunities to freshwater species and habitats, from new species colonisations.

## 3.14.1.7 Magnitude scores (N13)

Magnitude categories in Table 3.43 are based on expert judgement of authors (in agreement with CCRA reviewers) of low for the present day and therefore likely low magnitude impacts on species groups across all four UK countries (category: 'Minor impacts on or loss of species groups'). There is relatively little evidence available to inform assessment of this opportunity and this contributes to the lack of confidence, both now and in the future.

<b>Table 3.43</b> Magnitude scores for opportunities to freshwater species and habitats from new species colonisations					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	Low  (Low confidence)	Low  (low confidence)	Low  (low confidence)	Low  (Low confidence)	Low  (Low confidence)
<b>Northern Ireland</b>	Low  (Low confidence)	Low  (low confidence)	Low  (low confidence)	Low  (Low confidence)	Low  (Low confidence)
<b>Scotland</b>	Low  (Low confidence)	Low  (low confidence)	Low  (low confidence)	Low  (Low confidence)	Low  (Low confidence)
<b>Wales</b>	Low  (Low confidence)	Low  (low confidence)	Low  (low confidence)	Low  (Low confidence)	Low  (Low confidence)

## 3.14.2 Extent to which current adaptation will manage the opportunity (N13)

Many species will continue responding to climate change in a beneficial way without specific adaptation actions (reactive adaptation). Nevertheless, those actions implemented or proposed to enhance freshwater species at risk from climate change (see Risk N11) could also facilitate the arrival and establishment of beneficial new species, as well as benefiting existing native species. For example, Johnston *et al.* (2013) showed how the UK's SPAs could overall continue to provide protection for wintering waterbirds over the next 70 years in a scenario approximately consistent with 4°C global warming in the 2080s<sup>32</sup>, although the species at a site and assemblages could change.

<sup>32</sup> 50<sup>th</sup> percentile of the UKCP09 probabilistic projections with the A1FI emissions scenario in the 2080s (Murphy *et al.*, 2009). The projected changes in annual mean UK temperatures are within the upper end of the range for 4°C global warming in the UKCP18 derived projections (Gohar *et al.*, 2018).

To avoid repetition the adaptation measures and plans in Risk N11 are not covered here, however, it is worth noting that the opportunities are not usually taken into account, except in recognising that new species opportunities could enhance some sites or change community composition, with possible implications for site designations.

#### 3.14.2.1 Effects of current adaptation policy and commitments on current and future opportunities N(13)

The increasing interest in and use of natural flood management, e.g., by the EA (2018a), especially (for this risk) natural barriers, to manage small-scale floods may enhance opportunities for species.

#### 3.14.2.2 Effects of non-Government adaptation (N13)

No specific actions by non-Government actors were identified.

#### 3.14.2.3 Adaptation shortfall (N13)

It is not clear what additional policies may be needed to fully realise the benefits of climate change to freshwater habitats from new species colonisations. Many adaptation interventions to enhance freshwater habitats and species at risk from climate change as outlined in Risk N11 may provide support. At present, therefore, it is our view that this benefit will be realised to a certain extent in the absence of additional government intervention. However, this current assessment is based on a limited amount of evidence currently available.

#### 3.14.2.4 Adaptation Scores (N13)

<b>Table 3.44</b> Adaptation scores for opportunities to freshwater species and habitats from new species colonisations			
<b>Are the opportunities going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

#### 3.14.3 Benefits of further adaptation action in the next five years (N13)

Maintaining current adaptation as detailed in Risk N11 is in our view sufficient at the moment, unless there is a desire to promote any particular opportunities, such as the arrival of rare and/or iconic species, in which case specific actions might be needed in the next five years.

#### 3.14.3.1 Indicative costs and benefits of additional adaptation (N13)

Given the sustain current action urgency score (Table 3.45), there is no analysis of the costs and benefits of additional adaptation action.

### 3.14.3.2 Overall Urgency Scores (N13)

<b>Table 3.45</b> Urgency scores for opportunities to freshwater species and habitats from new species colonisations				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency Score</b>	Sustain current action	Sustain current action	Sustain current action	Sustain current action
<b>Confidence</b>	Low	Low	Low	Low

Because of the low current and projected magnitude for this benefit, and the view that additional intervention is not currently needed to realise it in full, this opportunity has been scored as Sustain Current Action.

### 3.14.4 Looking ahead (N13)

These opportunities are likely to continue into the future, but the actions currently being taken need to continue to include monitoring to ensure that species that are arriving do not spread disease or become invasive. They may also require an adjustment in the accepted species composition of habitats as part of conservation planning.

## 3.15. Risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures. (N14)

- Climate-related changes in UK seas have been especially marked by a warming trend, but also by a series of other shifts in the marine environment.
- Risk magnitude for this topic is projected to increase from medium at present to high in the future, although with notable uncertainties, and there is high potential for significant thresholds to be crossed causing irreversible changes.
- There is good evidence to suggest major changes will occur to the marine environment under scenarios of both 2°C and 4°C global warming by 2100, but it is very difficult to be precise on specific details due to multiple risk factors and the interconnectivity of marine ecosystems.
- In addition to temperature rises, risks are further compounded by expected changes in ocean acidification, stratification, oxygenation, salinity, and ocean currents. If CO<sub>2</sub> concentrations reached 940 parts per million (ppm) in 2100, either through emissions higher than consistent with current policies or less extreme emissions with strong climate-carbon

cycle feedbacks<sup>33</sup>, this would probably imply a reduction in pH of 0.3 or more. This would have major implications for many marine organisms.

- Current policy lacks detailed actions that include specific outcomes for the marine sector and plans for progress reporting that recognise the scale of climate change risks.
- More action is needed now to both manage existing risks and to better prepare for the scale of future change, such as for example, a stronger role and improved safeguarding for Marine Protected Areas.
- Changes in fisheries policy, international trade and access to markets resulting from the UK's departure from the UK will likely have major implications for this topic.

## Introduction

Marine ecosystems are impacted by climate change through both direct and indirect effects on the distribution and abundance of species groups, including plankton, shellfish, fin-fish, marine birds (seabirds and waterbirds), and marine mammals. In addition, negative impacts on priority habitats of high biodiversity value may occur, as through changes in either dominant or keystone species that have a vital role in habitat formation, or on the changing relationships between species and between species groups. This risk topic covers all negative impacts from climate change for the marine environment below the intertidal zone (the latter is covered under coastal environments: Risk N17) except for pests, pathogens, and INNS, which are separately assessed in Risk N16. As an island nation, the UK has a rich and distinctive marine environment with internationally significant biodiversity and ecosystem services, notably fisheries, that contribute to its economic and social wellbeing. The UK marine fishing industry was worth ca. £1.5 billion in 2017 (total catches were worth £980.1 million) and employed 23,000 people, although this is rather unevenly distributed between sectors and around the UK, mainly a few large ports, although small inshore fisheries also support local livelihoods and culture (Parliamentary Office of Science & Technology, 2019).

This topic area is one of the largest in the CCRA and when aggregated across the many contributing risk factors we consider that the evidence now indicates that more action is required. The magnitude of risk increases from medium at present to high in future, although with notable uncertainties because of the complexity of the environment and its response to multiple stresses. Nevertheless, we have good confidence in identifying that major changes will occur to the marine environment even if the details are less certain, and that these changes will be much more disruptive at higher magnitudes of climate change (therefore much higher in a 4°C warming scenario compared to 2°C), although significant changes at lower magnitudes are also inevitable and becoming increasingly apparent even at present. Hence, more action needs to be taken now to better prepare for these changes, and indeed as change is already occurring, these actions are very likely to have short-term as well as long-term benefits, both for biodiversity and ecosystem services including fisheries.

It is very likely that EU-exit will have major implications for this topic, most notably in terms of changes in fisheries policy (quota arrangements, regulations etc.) and the impact of any changes to

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<sup>33</sup> RCP8.5 concentrations pathway, which would either require CO<sub>2</sub> emissions above those consistent with current policies (see Introduction chapter: Betts and Brown, 2021) or a lower emissions scenario accompanied by strong climate-carbon cycle feedbacks (see Chapter 1: Slingo, 2021)

international trade and markets. At present though, finalised details on post-EU-exit arrangements are yet to be made. Similarly, any implications arising from the COVID-19 pandemic remain only speculative rather than sourced by evidence, although it is quite likely that some monitoring activities will have been adversely affected.

### 3.15.1 Current and future level of risk (N14)

#### 3.15.1.1 Current risk (N14)

Mean annual sea temperatures in UK waters have shown a consistent warming trend from the 1970s onwards superimposed on shorter-term fluctuations, with coastal sea surface temperatures now 0.6°C warmer in the most recent decade compared to the 1961–1990 average (Tinker *et al.*, 2020). In addition to these longer-term trends, changes in the mean climatological state of the North Atlantic Oscillation (NAO) have also led to changes in water current strength and circulation in the North Atlantic.

Accompanying this general warming trend have been more complex variations in salinity as the circulation of the Atlantic and shelf seas adjusts over multiple timescales. Hence, the salinity of surface waters to the north and west of the UK had increased since the 1970s until a more recent decline from about 2012, whilst deep water salinity in this region had freshened to about 2000 and then generally remained more stable (Dye *et al.*, 2020). By contrast, salinity of UK shelf seas shows no clear long-term trends that emerge from a pattern of considerable annual and decadal variability (excepting possibly more significant variation in the northern North Sea). On a shorter timescale, observational evidence clearly shows an extreme freshening event (unprecedented for 50 years) occurred in the subpolar eastern North Atlantic, west of the UK, from 2012 to 2016. Analysis has indicated that this freshening event was a distinctive feature of the eastern subpolar gyre and its interactions with adjacent circulation systems, caused by unusual winter wind patterns driving major changes in ocean circulation, including slowing of the North Atlantic Current and diversion of Arctic freshwater from the western boundary into the eastern basins (Holliday *et al.*, 2020). The relevance of these shorter-term variations, in addition to the long-term trends, is that the diversion of nutrient-rich and oxygen-rich subpolar waters into deeper troughs and basins (including the Rockall Trough etc.) can stimulate ecosystem productivity, at least temporarily, providing a distinct contrast to the incursion of warmer waters.

Previous CCRAAs have extensively evaluated the role of acidification caused by the oceanic uptake of CO<sub>2</sub>. Although average global acidification has increased by about 26% since pre-industrial time, present indications are that the reduction of pH has been more rapid in UK waters compared to the whole North Atlantic for which ocean surface measurements indicate a reduction in pH between 1995 and 2013 of 0.0013 units per year (Humphreys *et al.*, 2020). The ecological effects of acidification have been primarily inferred from experimental studies, either through reduced availability of calcite in shell-forming species or aragonite in corals, molluscs and algae. Maerl beds are also vulnerable to changes in pH which affects skeleton formation in addition to the impact of temperature on growth and reproduction. In addition, lowered pH has been found to depress feeding activity in deep-sea demosponges and increase foraging times of deep-sea echinoids.



Warming also means that seasonal stratification, which acts to limit mixing of shallow warmer waters and deeper cooler waters, is occurring earlier on average and lasting longer, although there are no clear long-term trends in strengthening of stratification (Sharples *et al.*, 2020). Changes in stratification have implications for plankton growth rates, species composition and distribution, hence affecting other species that depend on plankton, and may also potentially affect algal blooms.

Dissolved oxygen concentrations are also declining as a result of a decrease in the solubility of oxygen and increase in stratification frequency to that extent that some UK waters have been identified as oxygen deficient in late summer (although not hypoxic as with other European shelf seas) (Mahaffey *et al.*, 2020). Decreased oxygen concentrations and saturation may also be related to both physical processes and an increase in oxygen utilisation in the marine environment.

Studies of marine biological responses continue to show a very strong relationship with warming, including poleward shifts in species distributions across a wide range of taxa, changes in species phenology, and increased abundance of warm water species while cold water species decline (Poloczanka *et al.*, 2013; Genner *et al.*, 2017; Hastings *et al.*, 2020). Evidence is also available to indicate that species movements appear to be insufficient regarding the rate of climate change. In the North Sea, a recent study of benthic invertebrates has reported that their ranges would need to shift latitudinally by 8 km/yr to keep up with climate change, but populations are currently moving at a lesser rate of 4-7 km per year (Hiddink *et al.*, 2014). Changes in migratory patterns have also been detected, especially when linked to warmer winter temperatures.

For some species groups, the interaction of warming with other drivers noted above (salinity, acidification, stratification, oxygenation) is linked to further distinctive ecosystem relationships, although distinguishing multiple factors can be difficult, as discussed further below. In addition, other pressures are also continuing to have a detrimental effect on many species, notably overfishing and pollution, both in UK waters and internationally (State of Nature Partnership, 2019; IPBES, 2019; Moffat *et al.*, 2020). Climate change may also be interacting with fisheries pressures to further modify ecosystem relationships. For example, in the North Sea the expanded range and increased abundance of squid is considered likely to be a combination of warming effects and opportunistic adaptation due to declining fish populations, as has been also suggested for jellyfish abundance (van der Kooij *et al.*, 2016).

Harmful Algal Blooms (HABs) and associated eutrophication can also have negative effects on marine biodiversity, by depleting oxygen and reducing overall water quality. Although temperature is a key driver, the impact of climate change on HABs is complex due to the irregular influence of extreme weather events and nutrient runoff pollution from land, in addition to the potential influence of large-scale ocean currents (Wells *et al.*, 2015). In recent years, the areas most affected include the south-eastern North Sea, west coast of Scotland and Northern isles, and some coastal waters of the Celtic Seas, although monitoring is often linked to risk management reporting for shellfish and aquaculture activities (Bresnan *et al.*, 2020). Pollutant runoff and associated turbidity, both of which may be affected by increased heavy rainfall events, can also affect shallow-water seagrass habitats which have high biodiversity and ecosystem service value.

As highlighted in CCRA2, climate sensitivity is generally most evident at lower trophic levels, notably in marine plankton, but is typically more difficult to attribute with high confidence at higher trophic

levels due to the potential for multiple additional factors influencing species response. Plankton communities can show rapid responses to changes in nutrients, salinity, and temperatures, with changes in abundance varying regionally and by group for both phytoplankton and zooplankton. The Phytoplankton Colour Index (PCI) provides a proxy colour indicator of phytoplankton biomass whereas other indicators can also show abundance changes in phytoplankton and zooplankton. PCI for the northern North Sea during the most recent decade is 67% higher than in the 1960s, and over the last five years is 29% higher than the mid to late 2000s (State of Nature Partnership, 2019). Similarly, in the English Channel the PCI is 95% higher in the last decade and 18% higher in the last five years. Within groups of phytoplankton, regional differences are apparent. Increases in diatoms and dinoflagellates in the English Channel contrast with periods of decrease and overall stability in the northern North Sea which have been attributed to differences in trophic pathways and differing roles in the carbon cycle (OSPAR, 2017).

As also detailed in previous CCRAAs, the impact of warming seas varies geographically and by species, and also due to differences in interactions between species. Long-term increases in phytoplankton biomass of 21% and 13% have been reported in the coastal and open North Sea, respectively, between the 1980s and early 2000s. More recently however, estimates of primary production in the North Sea indicate a declining trend as well as changes in species composition and timing of seasonal events, with knock-on effects on zooplankton abundance and fish recruitment, including for cod, herring, haddock, whiting, sprat, and sandeel, as analysed through a standard recruitment index (Capuzzo *et al.*, 2018). These changes in phytoplankton growth and productivity are associated with both the direct effects of warming together with reduced mixing of surface and bottom water layers, which limits supply of nutrients from bottom waters reaching phytoplankton at the surface. The same study also found a significant correlation between decreased primary productivity and a decrease in riverine dissolved nutrient concentrations, notably reduced P in riverine inputs whereas N concentrations remain more unchanged, meaning some locations (notably the southern North Sea) have become more severely P-limited for phytoplankton growth.

Regarding zooplankton, small copepods, which tend to dominate the southern and central North Sea, appear to have declined in correspondence with reduced phytoplankton primary productivity (Capuzzo *et al.*, 2018). The total abundance of large copepods seems more variable but with a composition that has changed to an increasing dominance of more temperate species as a result of climate change. Over the last 50 years, total *Calanus copepod* biomass in the northern North Sea has declined by 70% due to regional warming, with resultant consequences for other dependent species. Warming temperatures in the NE Atlantic have also brought smaller warm-water copepod species into UK waters. Plankton species with warmer-water affinities (e.g., *Calanus helgolandicus*) have now moved northwards from the Celtic Sea to replace cold-water species (e.g., *Calanus finmarchicus*) in most of the seas around the UK. Changes in community composition and seasonal productivity have then been inferred to have cascading impacts at higher trophic levels including to fish and seabirds (see below). The abundance of planktonic larvae has increased in most areas associated with increasing temperatures (State of Nature Partnership, 2019). Similarly, increases in the abundance of the warm water kelp species, *Laminaria ochroleuca*, have been observed at sites around Plymouth, the Isles of Scilly and Lundy Island. Conversely, although evidence remains limited, warming has been linked to negative impacts on cold water corals (Moore and Smale,

2020), as for example through constraints on the dispersal and settlement of the larvae of the cold-water coral *Desmophyllum pertusum*.

For shallow-water shelf habitats, there is similar evidence for expansion of warm-water species (Moore and Smale, 2020). For example, there is good evidence for changes in UK kelp species abundance linked to altered sea temperatures, notably expansion and increased abundance of the warm-water species, *Laminaria ochroleuca*, including into more wave-exposed conditions.

Some nearshore habitats, notably seagrass beds are vulnerable to increased turbidity and pollution due to sediment runoff from land. Analysis of mapped UK seagrass extent against past records and habitat suitability assessments indicates that at least 44% of habitat has been lost since 1936, 39% since the 1980's (Green *et al.*, 2021). Shallow marine habitats, including seagrass beds, kelp beds, and serpulid reefs, are also vulnerable to disruption from increased turbulence due to changing patterns of storm frequency and intensity. Although evidence for long-term trends to increased storminess is often location-dependent, and also complicated by shorter-term variations such as through the North Atlantic Oscillation, some recent periods (notably winter 2013/14) have been notable for a clustering of successive cyclones following a storm track over the UK. This clustering can mean there is insufficient recovery time for the habitat, placing it in an increasingly weakened state and also vulnerable to other pressures.

Impacts on some species also have wider importance because they have a key ecosystem function, such as those species that help build habitat for other species ('ecosystem engineers'). Kelp are notable examples of these habitat-forming species (see also Risk N5 for carbon storage implications). For *Laminaria hyperborea* (the dominant habitat-forming kelp species in Scotland), modelled predictions showed northward expansions coupled with significant loss of suitable habitats at southern range margins (Assis *et al.*, 2016). Recent research from the western English Channel has shown that in addition to direct effects on biodiversity through shifts from cold-water species to warm-water species, indirect effects occur through modification of assemblages (both stipes and holdfast assemblages) which has led to reduction in both diversity and overall biomass (Smale *et al.*, 2015; Teagle and Smale, 2018). Moreover, analysis in the same regional location has shown that warm-water kelps had a much greater turnover of biomass (both accumulation and decomposition increased by ca. 80%) compared to cold-water species despite similar morphological and taxonomic affinities (Pessarrodono *et al.*, 2019). This was due to accumulation and decomposition of organic matter becoming year-round rather than over a much shorter discrete period, including a large increase in detritus formation and decomposition rate (increasing by a factor of 6.5). Such modifications to net ecosystem primary productivity will affect both the host ecosystem (including to higher trophic levels) and adjacent ecosystems due to nutrient transfer in currents. Further effects may occur through changes in sea urchin dominance (and barrens) for UK kelp populations but in addition to sea temperature, other environmental factors, and predation pressure on pelagic larvae, will influence sea urchin recruitment success.

In this context, other ecosystem engineers can be highlighted that through their sensitivity to changing climate conditions may have wider implications for biodiversity, ecosystem stability and functioning. This includes cold-water corals, horse mussel beds, maerl beds, seagrass beds, and other biogenetic beds and reefs, that act to modify and stabilise the sea floor, each creating a

distinctive habitat. In addition to the direct effects of ocean warming, these ecosystem engineers can be vulnerable to skeletal weakening associated with ocean acidification (Küpper and Kamenos, 2018; Moore and Smale, 2000; Jeffreys *et al.*, 2020).

Whilst fisheries show the general large-scale pattern of northward movement of species, historic overfishing pressures have been the dominant influence, although in the last 10 years some commercial fish species have increased in abundance from very low baselines. Warming and associated oxygen solubility appears to be influencing maturation age, growth rates, and maximum fish size, as warming tends to cause faster maturation and smaller maximum body size (Baudron *et al.*, 2014; Genner *et al.*, 2017; Wright *et al.*, 2020). Warming temperatures also affect timing of spawning among species, as has been observed with earlier spawning for cod (McQueen and Marshall, 2017). In some cases, differential warming responses between predator and prey have been inferred to be leading to a phenological mismatch across trophic levels with wider ramifications for ecosystem functioning, as for example with delayed development of the lesser (Raitt's) sandeel by comparison with earlier emergence of its copepod prey (Régner *et al.*, 2017, 2019). Meta-analyses and reviews of fisheries from different ecoregions continue to suggest that populations that have experienced more severe overfishing (in both intensity and duration) were most likely to be negatively influenced by warming, especially when this is combined with more rapid warming rates in excess of 0.2°C per decade (Free *et al.*, 2019; Pinnegar *et al.*, 2020).

Amongst UK demersal species, there have been increases in the populations of smaller-bodied, non-commercial species (Montero-Serra *et al.*, 2015), whilst pelagic species show a shift in recent decades from cold-water assemblages (e.g., herring) to warmer-water assemblages (e.g., mackerel, sardine and anchovy), probably further facilitated by changes in prey species (Lynam *et al.*, 2017). As noted above there is evidence that climate-driven declines in primary production and copepod arrival in the North Sea have led to declines in fish stock recruitment for some commercial species, including cod, herring, whiting and sprat. The combination of predator-prey (top-down) and resource-based (bottom-up) trophic controls has been suggested to explain the apparent slow recovery from overfishing of key species such as cod (Lynam *et al.*, 2017).

Another taxon that is potentially vulnerable to changing trophic interactions are elasmobranchs because of their reliance on zooplankton. For example, basking sharks gather in specific locations to feed on zooplankton at specific times of year, such as in the Sea of Hebrides between June and October (which is one of the main reasons for its designation as a prospective Marine Protected Area). However, further data on this taxon are required to more fully assess the climate change risk.

Shellfish are also sensitive to the effects of ocean warming and other pressures, both in the larval, juvenile and adult stages of their life cycle. Based upon this known sensitivity, we identify that the consequences may extend to potential catch implications for key species such as scallop, crab, lobster, and nephrops that can be of particular importance to some local coastal communities. However, although these sensitivities are known from species distributions relative to climate and other environmental conditions, there is as yet no clear data on long-term trends.

Since CCRA2, evidence is now increasing that declines in the abundance and nutritional quality of sandeels has reduced the breeding success and populations of some seabirds (notably surface-

feeding species such as kittiwake) although mechanisms remain to be fully established (Carroll *et al.*, 2015, 2017; MacDonald *et al.*, 2015; Regnier *et al.*, 2019; Mitchell *et al.*, 2020; Moffat *et al.*, 2020)). Sandeel populations seem to be affected by increasing sea surface temperature, the timing and strength of ocean stratification, and in mismatch in reproductive timings with availability of copepod prey (which are moving northwards), in addition to fishing pressures and pollution. Distinguishing causes and effects between these multiple stresses can therefore be difficult. Consequent effects on individual seabird species seem to be related to the location and timing of loss of prey species, and to a varying extent may be buffered in those seabird species that can access prey throughout the deeper water column rather than just surface waters. Improved use of tracking data and species distribution modelling is now being developed to provide more refined analysis of 'hotspot' locations that have a strong relationship with the breeding success of seabirds (Cleasby *et al.*, 2020).

There have also been other important changes in UK seabird populations (including breeding success) and distributions, including an ongoing decline in the UK seabird index defined based upon 13 key species (Defra, 2020b). These impacts are described in further detail in Risk N17.

Regarding marine mammals, the ranges of cold-water species, such as white-beaked dolphin, are contracting, whilst warm-water species are expanding (see Risk N15), but the role of climate change remains poorly understood. Adequate data is only available to determine trends for three cetacean species in the North Sea (harbour porpoise, white-beaked dolphin and minke whale), suggesting populations have remained stable (State of Nature Partnership, 2019). Better data is available for seal numbers, although the role of climate change also remains poorly understood. These data indicate that between 1994 and 2014 grey seal numbers increased, whilst harbour seals numbers decreased on the north and east coasts of Scotland but increased on the east coast of England and on west coast of Scotland. These changes in distributions are now being further investigated to confirm these patterns.

Finally, our assessment of known species sensitivities is that changes in ocean temperatures, circulation and salinity are very likely to be causative factors in the decline of some salmonids in UK rivers, notably the Atlantic salmon (cf. Olmos *et al.*, 2019), which has added importance because of its high economic and cultural value (see Risk N11) and also possibly some species of eel. Again, the exact causes are difficult to distinguish with high certainty due to the interaction of multiple factors acting on species with a complex life cycle, which also spend key stages of their lifetime in freshwater habitats (Risk N11).

#### 3.15.1.2 Future risk (N14)

UKCP18 and other future climate projections simulate continued ocean warming to 2100 in the range of 0.2°C to 0.4°C per decade, although with varying geographic patterns and punctuated by more extreme warming periods. This warming trend implies that it is almost inevitable that there will be major changes in UK marine biodiversity and fisheries, especially if the future pathway is towards the upper end of the climate projections. As highlighted above, warming also interacts with other marine phenomena stimulated by a changing climate, notably acidification, salinity, oxygen depletion, and changes in stratification and circulation patterns. In addition, non-climate socio-

economic drivers will continue to have an influence, including through changes in demand for fisheries and changes in pollutant loads, and cumulative pressures can be further exacerbated by coastal developments, aquaculture, offshore wind farms and other marine renewables. These multiple interactions and the current limited data on changes occurring in the present epoch (as described above) mean that details on the expected future changes remain rather uncertain despite their apparent inevitability (Cheung *et al.*, 2016). Furthermore, most studies of marine biological responses consider long-term changes in average temperature, and more rarely investigate the consequences of extreme events, including potential threshold effects, therefore this also remains an important source of uncertainty.

As described in detail for CCRA2, warmer waters have less oxygen solubility and carry less dissolved oxygen to lower parts of the water column, increasing the strength and duration of stratification, and further exacerbating the risk of low oxygen zones, including hypoxic conditions in coastal waters. Low oxygen conditions provide especially challenging conditions in the context of fish physiology and therefore will impact on the future of fisheries, although again important uncertainties remain (Townhill *et al.*, 2017). Oxygen concentrations in UK seas are projected to decline more than the global average, especially in the North Sea, with models indicating by 2100 the decline could be up to 11.5% (compared to a global average of 4%) (Mahaffey *et al.*, 2020). Projections for UK shelf seas also suggest that thermal stratification will occur for longer, typically starting a week earlier and ending 5–10 days later (Sharples *et al.*, 2020). In addition to oxygenation issues, reduced mixing of nutrients may have negative impacts on primary productivity whilst also increasing the duration, severity and distribution of HAB species and HAB events.

Regarding acidification, the Regional Ocean Acidification Modelling (ROAM) study, which used a high-end scenario of atmospheric CO<sub>2</sub> concentrations reaching 940 ppm in 2100<sup>34</sup> () has projected that average pH for the continental shelf could drop by up to 0.366 by 2100, with coastal areas having a greater reduction (Humphreys *et al.*, 2020). This change in pH (hydrogen ions) would imply an increase in acidification of over 100% compared to the present. The same high CO<sub>2</sub> concentrations pathway would imply bottom waters would become corrosive to more-soluble forms of calcium carbonate (i.e., aragonite) by 2100 although this pathway represents an upper extreme scenario. The same projections suggest up to 20% of NW Europe shelf seas may experience undersaturation for at least one month of each year with episodic undersaturation events beginning by 2030.

A consistent feature of future climate projections (including those associated with UKCP18) is the weakening of the Atlantic Meridional Overturning Circulation (AMOC) due to freshening in the Arctic and other related factors. The importance of this for the marine environment lies in its large-scale oceanographic influence on the transport of warmer sub-tropical water towards the UK and polar regions through the North Atlantic Drift (and Gulf Stream to the south). This is projected to affect the regional pattern of warmth and salinity in UK waters, strongly linked to the magnitude of global

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<sup>34</sup> RCP8.5 concentrations pathway, which would either require CO<sub>2</sub> emissions above those consistent with current policies (see Introduction chapter: Betts and Brown, 2021) or a lower emissions scenario accompanied by strong climate-carbon cycle feedbacks (see Chapter 1: Slingo, 2021)

warming, but with regional anomalies due to the dynamic circulation response (McCarthy *et al.*, 2020).

For salinity, most projections suggest that UK shelf seas will become less saline as ocean circulation is further modified, with the greatest salinity decreases indicated for the North Sea (Dye *et al.*, 2020). For example, one notable recent modelling study suggests that climate-driven change in the North Atlantic and Arctic oceans could reduce transfer of oceanic water to European shelf seas (Holt *et al.*, 2018). By 2100, this could make the North Sea function more like an enclosed estuary in status than an open-shelf sea with decreased salinity and oxygen levels and significantly increased temperature and stratification, resulting in potential major consequences for the existence of many species, especially if pollution and eutrophication problems continue and become exacerbated. More generally, future projections for increased stratification in the NE Atlantic due to oceanic thermohaline changes would have implications for a wide range of taxa, although evidence on this is limited (some tentative associations are discussed in 'Current risk' including seabirds and sand eels).

These changes have major implications for species and habitats of high conservation value. For cold-water corals and maerl beds, ocean acidification has potential to cause significant corrosion damage, particularly of the non-living structures that provide structural support for the living surface layer, although confidence again remains limited in future projections (Jeffreys *et al.*, 2020). Following the upper-end emissions pathway of RCP8.5 would imply substantial decreases in seafloor habitat suitability for cold-water corals in the North Atlantic, suggesting that ca. 85% of existing features would become exposed to increasingly acidic waters by 2060. This upper end pathway would also imply by 2080, that summer warming could exceed the thermal tolerance of the main reef-forming cold-water coral, *Desmophyllum pertusum*, at the Mingulay reef complex off NW Scotland (State of Nature Partnership, 2019).

Regarding future projections of impacts from acidification, an important uncertainty to recognise is the adaptive capacity of species to respond to this stress. Although several studies have investigated phenotypically plastic responses of species through shorter-term (usually single-generation) experiments, there has been rather less research on transgenerational responses and genetic adaptation, and this limited research suggests that longer-term adaptation responses may partly mitigate adverse effects (IPCC, 2019). Current evidence suggests that crustaceans will be more ecologically resilient against acidification as compared to lesser resilience with molluscs, but responses in fin-fish remain rather more uncertain.

The general pattern for future change is the further replacement of cold-water species with warm-water species, with the rate of change dependent on climate change scenario and regional sensitivities. For example, models project that cold-water kelp species could be lost from southern England and Wales by the end of the century (Moore and Smale, 2020). Future warming is also very likely to continue to shift the geographical distribution of primary and secondary plankton production northwards, also influencing oxygen production and ocean carbon storage (Genner *et al.*, 2017). Warming may further decrease mean plankton community body size, with consequences for fishes, and marine mammal and seabird populations, although these changing inter-relationships remain a major uncertainty. Individual species responses will depend on their physiology and thermal tolerance, which can then potentially vary further due to acclimation (over the lifespan of

the individual) and adaptation (over evolutionary time), influencing both species diversity and abundance, and interactions across trophic levels. It is also likely that thermal stress will increase the prevalence of disease in some species (see Risk N16).

For fisheries, rapid range shifts greater than 4 km per year are projected over the next century, with the shifts indicated to be more rapid for open water pelagic species than demersal species due to higher potential motility (Genner *et al.*, 2017). As discussed in detail in CCRA2, although expectations are generally that species composition will be substantially modified, implications for UK fish stocks and fish production remain uncertain and there is no clear consensus on the details of change beyond expected long-term declines in cold water species, such as Atlantic cod, to be replaced by warm water species (for opportunities see Risk N15) (Pinnegar *et al.*, 2020). However, a study of eight demersal North Sea species using a statistical model found these species were unlikely to move north to cooler waters, due to their dependence on non-thermal resources (including water quality, suitable depth and substrate) implying that 'new' demersal fisheries are unlikely to arise (Rutterford *et al.*, 2015). Instead, the thermal preference of species will determine local expansion or contraction of existing commercial species.

Recent evidence from modelling of coralline algae in Scottish waters has shown large-scale spatial declines in distribution under all IPCC RCPs (ranging from 38% decline under RCP 2.6 up to 84% decline under RCP 8.5), with the most rapid rate of decline up to 2050 (Simon-Nutbrown *et al.*, 2020). This modelling approach also indicates suitable areas for species presence that currently lack records of occurrence and also that refugia populations may persist in some locations despite climate change, both important issues for informing priority areas for future conservation efforts.

Similarly, process-based modelling on warming and acidification parameterised with experimental data has estimated substantial declines in UK catches of demersal, shellfish and pelagic fishes by 2050, especially due to decreased primary productivity, with losses compared to present projected to be ~£87 million per annum (Fernandes *et al.*, 2017). Detailed process-based modelling of key pelagic species in the NE Atlantic based upon their exploitation to maximum sustainable yield (MSY) has found that potential mackerel and sprat catches were projected to increase in both a RCP2.6 and RCP8.5 climate change scenario (Fernandes *et al.*, 2020). However, the same study found that, although herring and blue whiting catches were projected to increase under RCP2.6, decreases were projected for RCP8.5. Overall, this study found that potential catches increased in the northern area of the NE Atlantic but decreased in the southern area, due primarily to changes in temperature and primary production, and hence that shifting pelagic resources may destabilize existing international agreements and quota sharing. Furthermore, other modelling work also suggests climate change will modify fish community size-structure to the extent that current policy targets may become unviable (Queirós *et al.*, 2018).

Modelling is also further investigating the implications of future change for seabird populations, indicating that it is very likely that there will be major changes in species abundance and their distributions. For example, modelling has suggested that the North Sea could become an important wintering area for some species including common guillemot, razorbill, great black-backed gull and herring gull (Searle *et al.*, 2020). However, many species have strong ties to their traditional breeding colonies, which may constrain their capacity to move.



UK aquaculture is dependent on two core species, the Atlantic salmon and blue mussel. As both species are close to the southern limit of their European range, then future warming has implications in terms of loss of productivity through thermal stress, lower growth, reduced food conversion efficiency, and a higher incidence of parasites and pathogens (Risk N16). Warming may also reduce immunocompetence of farmed species (Callaway *et al.*, 2012). However, evidence describing impacts on future production in commercial systems remains limited. Research shows Atlantic salmon actively prefer to occupy a 16–18°C temperature zone within aquaculture cages, and they display an active avoidance of water warmer than 18°C, consistent with evidence suggesting that an optimal growth temperature range is 14–18°C (Oppedal *et al.*, 2011). Reductions in performance by 20–25% have been inferred when temperatures reach 16–20°C. Central future climate projections suggest temperatures will remain suitable for salmon farming in most existing areas until the end of the century and may increase growth rates, however warming would be increasingly likely to affect summer and autumn aquaculture in Northern Ireland and the south of Scotland. By contrast, a high-end scenario could result in summer sea temperatures consistently exceeding 18°C in most existing production areas by 2050. Rising sea temperatures is also likely to cause reduced dissolved oxygen availability in water, further impairing performance, and increasing hypoxia risk (Genner *et al.*, 2017).

Impacts have also been modelled for blue mussel production in Strangford Lough (Northern Ireland), with an average water temperature rise of 1°C predicted to lead to a 50% production loss, whilst an average rise of 4°C would lead to a 70% production loss (Ferreira *et al.* 2008). Acidification may reduce shellfish spat settlement but is currently considered to be unlikely to affect fin-fish farming (Callaway *et al.*, 2012).

The economic impacts of acidification on shellfish fisheries and aquaculture to 2100 has been estimated using different methodologies (Net Present Value - NPV; Partial Equilibrium - PE) and emission scenarios (medium emissions A1B; high emissions RCP8.5 scenario) (Mangi *et al.*, 2018). Using the NPV approach, the direct potential losses due to reduced shellfish production range from 14–28% of fishery NPV, which would equate to a potential annual economic loss of £3–£6 billion of UK GDP. Results using the PE model, which has probably more realistic assumptions, assessed the total loss from shellfish production and consumption at £23–88 million.

Further research is required to investigate changing parasite loads in aquaculture. For example, *Mytilicola intestinalis* which is a copepod parasite of the mussel *Mytilus edulis*, is known to depress feeding performance at water temperatures of 22–23°C in UK waters, which may become an increasing risk factor, especially for southerly locations, in a high climate change scenario. Warming seas may also allow establishment and spread of new pathogenic parasites and increased incidence of bacterial diseases, notably from *Vibrio* species (Callaway *et al.*, 2012) – these changing risks have important implications for human health (see Chapter 5, Risk H6: Kovats and Brisley, 2021).

### 3.15.1.3 Lock in (N14)

Fisheries management and its influence on the wider marine ecosystem may be susceptible to lock-in risks when catches are maintained beyond a sustainable level. Evidence has shown that fisheries are vulnerable to abrupt collapse in stocks when over-exploitation occurs, including excessive harvesting of juvenile fish, and this may be exacerbated by the additional pressures of climate change on fish recruitment. There are important socio-cultural factors involved within the fisheries sector, and these can mean that fishers continue to focus on particular species and fishing grounds despite declining stocks and the requirements for diversification.

It has also been suggested that designation of Marine Protected Areas (MPAs) may be susceptible to lock-in risks, particularly where these are set up on the basis of habitats associated with historic marine climate suitability that may become less suited in future (Watkiss *et al.*, 2019). Hence, MPA designation needs to also include the dynamic effects of climate change in setting conservation objectives. In some cases (although not all), physiographic features that influence high biodiversity value may give a clearer indication of future nature conservation potential rather than the past or present distribution of species and habitats: this approach is being developed for some MPAs in Scotland using larger-scale features such as ocean fronts, sea-mounts, shelf banks, shelf deeps, and continental slopes (e.g. Sea of the Hebrides, Southern Trench, Shiant East Bank) (NatureScot, 2021).

### 3.15.1.4 Thresholds (N14)

Thresholds are known to be important in the marine environment but usually poorly understood. In addition to temperature-based thresholds, such as through physiology and thermal tolerance limits, climate-related thresholds are postulated for salinity, oxygen demand and acidification. However, in each case the threshold will relate to an individual species and may be difficult to identify due to the interaction of multiple factors on that species.

The CCC Thresholds project (Jones *et al.*, 2020) assessed the impact of higher temperatures on cod stocks in UK waters using a threshold annual average sea bottom temperature of 12 °C. This analysis used data from a NW European Shelf simulation covering the time-period 2000 – 2099 in conjunction with the HadGEM2-ES climate model and high-end climate change forcing (RCP8.5) consistent with a 4°C world. As the temperature threshold shifts northwards with global warming, the assumed climate space for cod is defined to become restricted to Scottish waters in the Atlantic and to the northern North Sea (northern parts of English waters only and Scottish waters). The same study also assessed thresholds in terms of changing Pacific oyster distribution which can be interpreted as an opportunity (Risk N15) or as an invasive threat to existing species (Risk N16).

In addition to thresholds occurring when incremental change reaches a critical level, we can infer based upon known sensitivities that it is highly likely that the increased frequency of some types of extreme events (e.g., marine heatwaves; deoxygenation; freshening and salinity pulses) will be responsible for triggering irreversible changes including species extirpation or even potentially larger-scale extinctions. In addition, actual temperature thresholds may be lower than assumed when just using a simple relationship with maximum temperature, because physiological thresholds

can exist across different stages of a species life cycle, especially for fish, hence these ‘thermal bottlenecks’ can further exacerbate a species inherent vulnerability (Dahlke *et al.*, 2020).

There is also evidence as indicated by a general review of the evidence (IPCC, 2019) that critical thresholds for some marine ecosystems will be reached at relatively low levels of global warming, therefore almost certainly in a 4°C warming world, but possibly averted in a 2°C world. Globally much attention has been focussed on warm-water corals but other sensitive ecosystems that are relevant from a UK perspective include kelp forests and seagrass communities (Smale, 2020), especially as related to a shift from cold-water species to dominantly warm-water species and resultant influence on ecosystem functioning (Teagle and Smale, 2018; Pessarodona *et al.*, 2019). Furthermore, it is very likely that there are ecological thresholds associated with changes in other climate-related phenomena, such as acidification and deoxygenation, and moreover that these critical thresholds may also have an ocean-depth related component (IPCC, 2019).

### 3.15.1.5 Cross-cutting risks and inter-dependencies (N14)

Marine ecosystems are fundamentally interconnected therefore the general scientific consensus, both globally and for the UK (IPCC, 2019; MCCIP, 2020), is that climate change risks to marine biodiversity and ecosystem functioning can be anticipated to have a severe effect on fisheries production and hence on fishing communities and businesses. Similarly, negative impacts on fisheries can have consequences throughout the whole ecosystem as predator-prey relationships are modified. In addition to fisheries, marine ecosystems provide many other ecosystem services including for the carbon cycle and oxygenation, and for their cultural benefits. The likelihood of major reorganisations in marine ecosystems, including through large-scale changes from weakening of AMOC (McCarthy *et al.*, 2020), therefore, is very likely to lead to multiple cascading and feedback-type effects both on land and at sea.

Risks to fisheries have particularly important implications for those coastal communities that have a high stake in this sector, either through direct involvement in fishing or aquaculture, or related activities such as processing or distribution. Changes to fish stocks or the effects of changes in policy may therefore have severe localised impacts based upon these interdependencies, and this may also extend to exacerbation of inequalities in those communities (see Chapter 5: Kovats and Brisley, 2021). In addition, climate-related movements in fish stocks, such as shifts further north in commercially important cold-water species, have implications for fisheries businesses (see Chapter 6); for example, this may require further travel by fishing vessels, or longer-term decisions such as relocation of operational bases or processing facilities. Furthermore, there are cross-cultural implications for marine heritage (e.g., archaeology) and for the diverse cultural interactions that occur between coastal communities and the marine environment (e.g., traditional fisheries; locality foods based upon fin-fish, shellfish or other produce).

These cross-cutting interactions have been further investigated in terms of the wider impacts of Marine Protected Area designation, showing that these have an important influence not only for biodiversity objectives but also for wider socio-economic issues, including for fisheries, aquaculture, seafood processing, tourism, and community engagement with marine issues (Scottish Government, 2020b).

#### 3.15.1.6 Implications of Net Zero (N14)

The marine environment has a key role in the carbon cycle with marine habitats such as seagrass beds and many marine species actively sequestering carbon, although the rate of sequestration is likely to be affected by warming of the seas and by acidification impacts on both individual species and community interactions. Some species, communities, and habitats will be more resilient and adaptable to these changing conditions, and this will also be influenced by the presence or absence of other (non-climate) pressures. Marine environments are not currently included in national GHG inventories and therefore the considerable potential they provide to reduce GHG emissions, including through further habitat restoration, is not included currently in the CCC (2020) Net Zero scenarios (ostensibly, this is due to the challenges in obtaining robust data for emissions/sequestration rates but as noted elsewhere for the LULUCF sector, uncertainty in spatial/temporal variations is inherent to the natural environment). Conversely, further degradation of marine ecosystems acts to reduce their carbon storage capacity and contributes to atmospheric CO<sub>2</sub>, therefore a more complete assessment of progress towards Net Zero would include this in terms of balancing GHG accounts through national inventories.

In addition, the Net Zero scenario features a large expansion in offshore renewables, which may have implications for marine biodiversity, notably seabirds, through collision and displacement unless carefully planned (e.g., Peschko *et al.*, 2020). Research is still in the early stages of assessing these impacts, but in some cases they may also have positive impacts: for example, analysis by Slavik *et al.* (2019) of blue mussel (*Mytilus edulis*) and other epifauna accumulations on turbine structures found that they could lead to significant changes in regional annual primary productivity (up to 8%) in the wind farm area, and similar magnitude changes in daily productivity also at locations farther away from the wind farm.

#### 3.15.1.7 Inequalities (N14)

As identified above, changes in fish distribution and impacts on fisheries may have resultant impacts for communities (usually in coastal areas) that have a high degree of dependence on these resources, as has occurred through such changes in the past. This may have important implications for progress on addressing societal inequalities in these vulnerable locations, although at present we have limited evidence as to how these inter-relationships between socio-economic and climate change factors may be affected at present and in the future (see also Chapter 5: Kovats and Brisley, 2021).

#### 3.15.1.8 Magnitude scores (N14)

Magnitude categories in Table 3.46 are based on expert judgement and assessed in terms of existing or expected impacts on biodiversity (including viable metapopulation sizes), ecosystem functioning, and ecosystem services (including fisheries but excepting carbon storage – Risk N5). This approach is also followed because indicators based upon species numbers or habitat area are only crudely indicative of systemic risks. Risk magnitude is assessed as at least medium at present (this is a

conservative assessment based upon available evidence) and increasing to high in the future under all climate projections. Confidence is medium (present) and low (future) due to limits on evidence availability (including some conflicting results) compared to the complexity of the marine environment, including key uncertainties such as species and trophic interactions and their effects on ecosystem function.

**Table 3.46** Magnitude scores for risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	High	High	High	High
	(Medium confidence)	(low confidence)	(Low confidence)	(low confidence)	(low confidence)
<b>Northern Ireland</b>	Medium	High	High	High	High
	(Medium confidence)	(low confidence)	(Low confidence)	(low confidence)	(low Confidence)
<b>Scotland</b>	Medium	High	High	High	High
	(Medium confidence)	(low confidence)	(Low confidence)	(low confidence)	(low confidence)
<b>Wales</b>	Medium	High	High	High	High
	(Medium confidence)	(low confidence)	(Low confidence)	(low confidence)	(low confidence)

### 3.15.2 Extent to which current adaptation will manage the risk (N14)

#### 3.15.2.1 Effects of current adaptation policy and commitments on current and future risks (N14)

##### 3.15.2.1.1 UK-wide

As described below, the importance of the marine environment is increasingly recognised in national adaptation policies and fisheries also feature prominently, although detailed actions (that also include specific outcomes and plans for progress reporting) to address climate change risks remain rather limited based upon evidence available for this assessment. More especially, the plans are also constrained in terms of being robust against the full range of potential climate change pathways, hence limitations are particularly apparent in the context of managing risks at higher rates of climate change including in a 4°C world. In many regards, the scale and interconnectivity of

the marine environment acts to limit the range of viable adaptation options, but this further emphasises the importance of facilitating natural adaptation processes through maintaining and enhancing biodiversity (at all levels from genetic to ecosystems) and ensuring habitats are in favourable condition (including restoration where necessary).

The UK was a signatory to the Aichi 2020 targets agreed under the UN Convention on Biological Diversity (CBD, 2020) but has recognised that it has not met target 6 on '*Sustainable management of marine living resources*'. Although some UK fish stocks are showing signs of recovery in response to sustainable fisheries measures, not all stocks are yet fished at sustainable levels, and secondary effects continue through other ecosystem interactions (combined top-down and bottom-up effects: Lynam *et al.*, 2017 as discussed in section 3.15.1.1). New targets are now being set for 2030 under the same UN Convention on Biological Diversity. The UK is also a party to the OSPAR Convention to protect and conserve the NE Atlantic and its resources.

The official UK Government indicator (Defra, 2020a) shows that the percentage of fish stocks fished at or below levels considered to be capable of producing Maximum Sustainable Yield has increased from 7% in 1990 to 49% in 2017, and 33% of quota managed fish stocks are still reported as being harvested unsustainably (the status of the remainder is defined as 'unknown').

The UK Government's last assessment of progress towards Good Environmental Status (GES) under the EU Marine Strategy Regulations confirmed GES will not be met by 2020 for fish, commercial fish and shellfish, benthic habitats, breeding seabirds, and for non-breeding waterbirds in the Celtic Seas. GES had been achieved for four pressures (including eutrophication and contaminants), was partially achieved for four components of biodiversity, but was not achieved for three pressures and three components of biodiversity (including both fish and commercial stocks). Obligations that contain reference to condition monitoring for marine environmental change, including as previously required for the EU Water Framework Directive and EU Marine Strategy Framework Directive, will require further assessment with regard to the implementation of new UK legislation in the near future.

Marine Protected Areas (MPAs) have been identified as a key mechanism for enhancing resilience to climate change through high biodiversity and by providing ecological connectivity and space for facilitating range shifts. There has been a recent large increase in the extent of MPAs, especially since 2010, although monitoring of conservation actions in these areas is usually still in the earlier stages (Solandt, 2018; Tinsley, 2020). Modelling suggests there may be substantial warming-related changes to habitat within MPAs by 2100, which may lead to their current locations being suboptimal for the target 'feature' species or habitats used for their designation (Gormley *et al.*, 2013). Management measures have been documented in 60% of MPAs but only fully implemented in 10% of sites up to 2019 (State of Nature Partnership, 2019). In Scotland for example, 27 MPAs have specific fisheries measures in place and for a further 33 MPAs measures have been identified or are in the process of being developed in consultation with the fishing industry and other stakeholders. Other area-based measures, at 5 locations including voluntary reserves, restricted fisheries areas and fisheries closures, and safety exclusions zones around offshore windfarms, are also considered to contribute to the Scottish network. Despite these examples of progress and recent policy announcements on new MPAs (see below), recent assessments have identified a shortfall in

delivering the conservation objectives associated with the MPA network as represented by continued biodiversity loss (State of Nature Partnership, 2019).

Challenges remain regarding a successful implementation of MPAs. These include the lengthy time between design, objective setting, and plan implementation which acts to hinder adaptive management (Álvarez-Fernández *et al.*, 2020). In addition, defining a baseline assessment can be hindered by lack of data and the metrics used to define ‘good’ environmental status can be disputed (Solandt, 2018). Furthermore, although MPA networks may cover a large proportion of the seabed, the area within them for which management measures act to prohibit damaging fishing activity is typically much smaller which is especially of relevance for benthic communities affected by bottom fishing (Langton *et al.*, 2020). Hence, although fishing pressure is not necessarily reduced, the protected areas have particular value in protecting relatively pristine habitats from new fishing pressures, commonly those that have a higher ruggedness compared to other areas.

The new UK Fisheries Act 2020 has now been ratified by the UK Parliament. New provisions in the Act are designed to ensure that climate change impacts on fisheries will be accounted for including a new objective to move towards ‘climate-smart fishing’, although details for implementation of this are not yet available. The Act will provide a legal basis for all fish stocks to be harvested at sustainable levels including a sustainability plan for each fish stock that includes ‘the need for fish and aquaculture activities to adapt to climate change’. The Act also recognises that fish stocks are mobile, and that many are ‘shared stocks’ requiring negotiation with bordering countries to agree effective management, although the principles for this as they relate to climate change adaptation are yet to be established.

Regarding adaptation progress for all UK countries, a major constraint in assessing progress is the limited monitoring and data collection, both for biodiversity and fisheries (Frost *et al.*, 2016). For fish stocks, about 12% are identified as being of unknown status, including nearly all elasmobranch (shark and ray) stocks, whilst understanding of catches remains poor in the context of climate change and sustainable yields due to low levels of effective monitoring at sea (State of Nature Partnership, 2019).

#### 3.15.2.1.2 England

In England, nationally important habitats and species are protected through Marine Conservation Zones (MCZs) which act as designated MPAs and have been developed through a phased approach, including 27 sites in 2013, a further 23 sites in 2016, and a more recent commitment (2018) to create 39 more sites. However, detailed plans for most of the sites that would include adaptation objectives have yet to be published. The recent Benyon report for England has recommended the rapid creation of Highly Protected Marine Areas (HPMAs) in which all “extractive activities”, including dredging, sewage dumping, drilling, offshore wind turbine construction and even catch-and-release recreational angling, will be prohibited (Benyon *et al.*, 2020). Marine planning in England is administered by the Marine Management Organisation (MMO) which brings together planning, licensing and enforcement based upon a series of 10 plan areas. Fisheries are intended to be managed according to the provisions of the new UK Fisheries Act 2020.

Defra have also funded a marine pioneer project that has investigated new approaches to sustainable marine management consistent with the goals of the 25-YEP, including increased use of natural capital and the ecosystems approach, based upon case study areas in North Devon and Suffolk (MMO, 2021). This project identified key barriers regarding a lack of integrated planning and a chronic shortage of data to inform MPA management, and has provided a series of recommendations to address these barriers.

#### 3.15.2.1.3 Northern Ireland

The Northern Ireland Marine Plan was published for public consultation in April 2018 and includes climate change as one of its core components. The MPA network has been significantly expanded in terms of designated area (now at 2566km<sup>2</sup>) in recent years and the next stage will involve identification of necessary management measures to bring the network into 'favourable condition' (currently only 115km<sup>2</sup> is assessed as favourable). Northern Ireland is also involved in the MarPAMM project to trial new approaches to MPA management. Regarding fisheries, there was a consultation in 2014 for a new Fisheries Bill however the Fisheries Act (Northern Ireland: 2016) covered the enforcement of EU rules rather than a full update. With regard to Water Framework Directive *E. Coli* standards, only 2 out of 9 shellfish water protected areas (SWPAs) achieved compliance in 2019.

#### 3.15.2.1.3 Scotland

SCCAP2 (Scottish Government, 2019) identifies key actions for this risk as linked to the National Marine Plan, including that the use of the marine environment is spatially planned where appropriate and based on an ecosystems approach and adaptive management. It is also noted that fisheries will be managed taking into account changes in species distribution and abundance, and also including implementation of the vision proposed by the 2015 Inshore Fisheries Strategy; a key indicator for the SCCAP2 will be mortality consistent with achieving maximum sustainable yield. A climate change subgroup of Scotland's Farmed Fish Health Framework is developing further adaptation actions for the aquaculture sector, including monitoring of acidification impacts. The Scottish Government is also currently in consultation with stakeholders to inform and develop Scotland's Future Fisheries Management Strategy using an ecosystems-based approach. The additional designation of 4 new Nature Conservation MPAs and 12 SPAs will extend protected area coverage of Scottish seas to 37% with the aim of further decreasing existing pressures and to enhance overall resilience. The 2018 Parliamentary Report on the Scottish MPA network noted fisheries management measures in place and further measures being developed, as well as showing current progress towards achieving MPA objectives. A more recent report from Marine Scotland (Moffat *et al.*, 2020) has synthesised monitoring of the wider socio-economic impacts from MPAs based upon 4 case study locations, highlighting both positive and negative effects of MPA designation (including for fisheries, food processing, tourism, public engagement etc.) and their interactions with other changes, including climate change. Conservation and Management Advice documents that develop site-specific Conservation Objectives for each MPA, including climate change effects, have been drafted but are not yet published for the full suite of MPAs. Innovative approaches to MPA management planning are also being trialled in some areas (e.g. Outer Hebrides; Argyll) through the MarPAMM project. Further measures are also being developed (led by Marine Scotland) to reduce pressures (including fisheries) on sensitive Priority Marine Features



(PMF) outwith the MPA network. A PMF Review currently in progress aims to review the current PMF list (including to identify species at greater risk from climate change or important contributors to climate change mitigation), and to consider potential additions, including marine birds.

The Scottish Marine Assessment 2020 (SMA2020) has recently reported on the state of the marine environment, further confirming the threat from loss of biodiversity and climate change, including declining area of priority habitats in some marine regions, but also highlighting the challenges of interpreting the scale of impacts based on too few ecosystem monitoring sites and of understanding cumulative impacts (Moffat *et al.*, 2020). Although this means confidence in interpreting impacts remains low, current condition monitoring indicates that priority seabed habitats (e.g. seagrass, flame shells; mussel beds) have declined in extent, especially in parts of western Scotland and the Moray Firth (based upon seabed surveys in MPAs between 2011-2019), meaning current objectives to ensure 'no net loss' of priority habitats are under threat. The reasons for this remain to be fully established but have been attributed to overfishing and fishing gear, pollution sources, or potentially climate effects and climate change. The MPA assessment in SMA2020 also does not include the recent expansion in designation of MPAs since the end of 2018, for example the West of Scotland MPA and others designated in 2020.

#### 3.15.2.1.4 Wales

The new National Marine Plan (Welsh Government, 2019d) introduces a 20-year guiding framework to support sustainable decision-making for the seas of Wales, recognising the importance of ecosystem resilience, the value of biodiversity and the need to tackle climate change, also taking forwards EU Habitats Directive commitments (Conservation of Habitats and Species Regulations 2017). However, detailed implementation plans are yet to be provided and there is no specific mention of addressing impacts of climate change on fisheries within the Fisheries Sector Objective or for marine species. The Wales Marine Fisheries Advisory Group is a government/stakeholder group to discuss key policy issues but minutes show climate change risk has not been a priority on the agenda. Similarly, no explicit mention of climate change adaptation is provided in the MPA strategic Framework. The 'Prosperity for All: A Climate Conscious Wales' programme report identifies 5-year marine sector actions to improve the condition of wider marine ecosystems via Marine Protected Area Management (MC3) and research on marine ecosystems, marine services and marine heritage (MC4). For fisheries, the 'EU-exit and Our Seas' document outlines how Welsh Government will support the fishing industry and sector in its approach to developing fisheries post EU-exit using sustainable development principles focused on ecosystem services and long-term fisheries planning, including new opportunities and diversification (as also linked with the NRW Welsh Marine Evidence Strategy 2019-25). A variety of co-funded marine projects are also expected to enhance the evidence base (but not available at present) including the Bluefish project to assess vulnerability of commercial fish and shellfish in the Irish and Celtic Seas.

The risks from climate change are recognised in the Marine Area Statement published by Natural Resources Wales, including a specific theme for 'Building resilience of marine ecosystems'. The area statement details a number of goals, including shared responsibility with key stakeholders, improved research and understanding, and 'targeting resources' when an assumed good understanding of the issues is present.

### 3.15.2.2 Effects of non-Government adaptation (N14)

Regarding fisheries, Seafish, the industry trade body, produce annual watching briefs with the aim of informing the sector on latest developments in science, monitoring and policy. A previous Seafish report produced under the Adaptation Reporting Power conducted an initial risk appraisal for the sector. Whilst recognising increased exposure for the sector, this horizon-scanning assessment generally concluded that climate change from an industry perspective was a longer term and less urgent priority at that time compared to other issues (Garrett *et al.*, 2015). Much of the emphasis to-date has been on voluntary initiatives, but these require active uptake by the fishing industry, and we have very limited information on how this is happening or contributing to adaptation progress, especially in the context of modern fisheries technology.

With regard to biodiversity conservation, restoration initiatives established through local marine partnerships increasingly have a climate change component and are integrated with matching long-term objectives, as for example with the Seagrass Ocean Rescue project which is trialling seagrass restoration at Dale Bay, west Wales. In England, a broad-scale assessment of potential restoration/recreation sites for seagrass and biogenic reefs has been developed to provide a basis for more detailed appraisal and implementation at local level (MMO, 2019). Similarly, the DEEP project in Scotland is aiming to restore oysters to the Dornoch Firth with the resulting biogenic reef also have benefits for water quality in addition to biodiversity.

Natural adaptation processes, aided by human activities (intentional or unintentional), can also produce unexpected surprises in the marine environment. For example, native oyster assemblages have recently been found in Belfast Lough (Northern Ireland) after being absent for more than 100 years. It is believed that the most probable explanation for this change is that adult oysters were introduced through commercial Blue Mussel fisheries and they have subsequently become established in small colonies, possibly further benefiting from recent bathymetric and hydrodynamic changes through the deepening of the central shipping channel (Smyth *et al.*, 2021). Another potentially important example is evidence that suggests kelp in coastal waters can help rehabilitate their immediate environment by lowering the acidity levels, which if supported by further investigation could provide a natural buffer against increasing acidification risks (Silbiger *et al.*, 2018).

### 3.15.2.3 Barriers preventing adaptation (N14)

In fisheries, market forces and the pressures to increase production can be in conflict with long-term sustainability objectives. These are often accompanied by political pressures, as related to national fishing quotas, which can act against the international collaboration needed to manage mobile fish stocks across territorial boundaries. These challenges are especially exemplified when fish move to new areas because the process of negotiating quotas and matching these to changing fish population distributions and sizes continues to be an uneasy compromise between science and political expediency (Scottish Parliament Information Service, 2018). There are also important socio-cultural factors underlying attitudes to change in the fishing industry and in local fishing communities (e.g. Reed *et al.*, 2013). These cultural norms and their influence on decisions such as

gear investments predispose fishers to target specific stocks or areas, hindering attempts to encourage diversification and other forms of adaptation.

For both biodiversity and fisheries, the complexity of marine ecosystems is a major challenge for effective adaptation, especially due to current constraints on monitoring data and therefore understanding of processes. Management decisions are typically based on simplified indicators which may not necessarily be representative of the wider ecosystem as for example with lack of knowledge on the vast majority of unmonitored and unregulated fish populations. This means that management plan objectives in MPAs and other strategic plans are often generic, subject to lengthy delays and rather static (Álvarez-Fernández *et al.*, 2020).

For some years, Wales and Ireland have benefitted from projects funded under priority 2 (Adaptation of the Irish Sea and Coastal Communities to Climate Change) of the EU Ireland-Wales Programme 2014-2020. While the impacts of EU-exit are not yet fully understood, the loss of this funding could have important implications for ongoing collaboration and monitoring of change in the Irish Sea.

#### 3.15.2.4 Adaptation shortfall (N14)

While there is an increasing recognition of the importance of the marine environment in national adaptation policies and of climate change in marine plans, there is still a lack of detailed actions to address climate change risks that include specific outcomes and associated plans for progress reporting. Notable examples of this shortfall are the limited development of targeted adaptation plans for both individual MPAs and the protected area network as a whole, and for fisheries both in terms of individual species and their interactions with other species. At present, there is limited detail on how climate change adaptation will be included in the fisheries management plans defined by the new Fisheries Act 2020. There are also limitations in existing condition monitoring which hinder robust adaptation planning. We assess there to be an adaptation shortfall for all UK waters (England, Scotland, Wales, and Northern Ireland), although confidence remains low due to limited available evidence on adaptation actions.

#### 3.15.2.5 Adaptation Scores (N14)

Table 3.47 Adaptation scores for risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

### 3.15.3 Benefits of further adaptation action in the next five years (N14)

Although adaptation objectives are sound in principle, including recognition of the need for a shift towards ecosystem-based management, our assessment is that they are also rather general and require both more expeditious implementation of current actions and additional initiatives to manage more effectively changes in risk. These issues are especially relevant for actions that seek to enhance natural adaptation in ecosystems because the scope for human intervention is usually more restricted in the marine environment (including schemes such as species relocation that are employed in terrestrial/freshwater environments). A priority should therefore be actions that reduce other environmental stressors, including pollution and overfishing, as recognised by MPAs and recent proposals to designate Highly Protected Marine Areas (HPMAs – see Benyon *et al.* 2020), and to enhance both their individual and collective (network) functionality through improved incorporation of clear objectives for climate change adaptation. New approaches to test application of these principles in practice are now being trialled, including the Defra marine pioneer case studies (North Devon and Suffolk), which have provided innovative suggestions for enhancing the marine environment (MMO, 2021) and through which ecosystem-based adaptation could be further incorporated.

In fisheries, much could be further accomplished by better implementation of existing measures through improved management and institutional arrangements (policy; legal; fisheries planning; conservation objectives; risk preparedness) (Poulain *et al.*, 2018; Gaines *et al.*, 2018). Diversification into new species and avoidance of negative by-catch losses will require gear and catch-method innovations, including new information-sharing networks to better target new species and avoid other species, particularly in mixed stocks with changing composition. This is likely to require further realignment of incentives to support sustainable fishing, including through further development of Ecosystem-based Management (EBM) for which a range of practical approaches have now been investigated in different contexts (e.g. Borja *et al.*, 2016). Pressure on existing stocks may also be alleviated by schemes to encourage the UK public to diversify their choice of fish beyond a few familiar species (notably cod and haddock) and through further development of certification schemes to indicate sourcing from sustainable sources (e.g. Marine Stewardship Council standard: MSC, 2020).

Enhanced proactive adaptation also requires establishing a sounder conceptual and management basis for key indicators such as ‘maximum sustainable yields’ (MSY) in the context of both short-term climate variability and longer-term climate change, including anticipatory application to new species in UK or international waters. In addition, MSY needs to be better framed within the context of ecosystem-based management (EBM), rather than individual species-specific targets in isolation, recognising also habitat needed for both the stock fish and other interdependent species to function. Nevertheless, it also needs to be recognised that the complexities of EBM may necessitate long lead-times for implementation, and that effective management of stocks also will require continued and probably enhanced international cooperation.

Improvements in adaptation for both biodiversity and fisheries are also strongly linked to better monitoring of ecological changes and their relationship with the physical environment (Mieszkowska *et al.*, 2014). Long-term assessment of ecosystem restoration projects is essential but

complex because ecological processes such as succession act to alter the consequences of restoration through time, particularly in highly dynamic ecosystems (Boerema et al., 2016). Monitoring is very likely to benefit increasingly from enhanced use of remote sensing and its use in combination with other observations to establish improved time series and spatial data. A further benefit from monitoring is likely to be better use of forecasting systems to understand and predict variability over different timescales, from seasonal to multi-annual, and hence their use in both fisheries and biodiversity management (e.g. for setting fishing quotas).

#### 3.15.3.1 Indicative costs and benefits of additional adaptation (N14)

There is more information emerging internationally on adaptation options for fisheries (Poulain et al., 2018), although most of these are extensions of existing actions including institutional adaptation (policy, legal, fisheries management and planning [including conservation and protection]), diversification (within and between the sector), risk preparedness and reduction. There is also information on the costs and benefits of these options (FAO, 2019). One study, Jones et al. (2015), identifies the net economic benefits of UK fishing fleets adjusting to the shifting fish stocks. It finds that net present value would fall in the situation where the fishing areas allowed under the Exclusive Economic Zone (EEZ) were retained as currently drawn. The study calls for investment into adaptive capacity within the industry. Watkiss et al. (2019) made an initial assessment of potential costs and benefits of some adaptation options for UK fisheries. They identified the potential benefits of an adaptive management approach for the fisheries sector, with a scale up in monitoring, scientific information and awareness raising, subsequently including this information in regular updates of fisheries policy (e.g. to set maximum catch potential for current species, include new species in policy) alongside awareness raising in the fishing sector. The Watkiss et al. (2019) study indicated that an adaptive management strategy would have positive benefit to cost ratios, through the value of information and enhanced decisions taken. It also looked at the potential costs and benefits of increasing MPAs to improve the marine environment in the face of climate change (more marine areas – with full protection – to deliver the same level of ecosystem service function/benefit), drawing on the economic literature on MPAs (Heal and Rising, 2014; Kenter et al., 2013; eftec, 2014; European Commission, 2017). This indicated that there would be net economic benefits of additional MPAs. Finally, it considered the question of whether other options might be introduced to ensure maximum sustainable yields are maintained under climate change, or to consider stricter policies. This found such measures would involve complex issues because of trade-offs (i.e. between enhanced efficiency and effectiveness of the fishing industry, versus greater pressure on maximum sustainable yields).

#### 3.15.3.2 Overall urgency scores (N14)

The evidence above suggests that major changes will occur to the marine environment under both 2°C and 4°C warming trajectories. Each of the UK administrations recognises the high importance of the marine environment and for seas and oceans to be good and sustainable condition, consistent with international agreements. However, current policy is rather generic in its commitments and lacks actions in sufficient detail to address these risks, notably targeted plans and associated measures to enhance and protect marine habitats and to urgently reduce fishing pressures so that

there is more scope to maintain fisheries at a sustainable level despite the increased challenges from climate change. Risks to this topic therefore have been assessed as 'More action needed', as further intervention is required across the administrations to better prepare for these changes, and indeed to better manage current changes.

<b>Table 3.48</b> Urgency scores for risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Medium	Medium	Medium

Additional actions include:

- Further development and regulation of the MPA network as associated with present biodiversity requirements and, importantly, expected future shifts in species distributions and implications for ecosystem functioning.
- Further reduction of non-climate pressures (overfishing, pollution etc.) to maximise potential for species and habitats resilience.
- Further development of habitat restoration initiatives.
- A clearer assessment and implementation of sustainable fisheries yields in the context of present and future climate change, and the wider ecosystem.
- Improved monitoring schemes to better assess progress on biodiversity and fisheries goals.
- Further research on the climate sensitivity of trophic interactions from plankton to fisheries, seabirds and mammals.
- Further research on the sensitivity of UK aquaculture species to multiple climate change drivers.

#### 3.15.4 Looking ahead (N14)

Many important knowledge gaps remain in terms of understanding the combined effects of ocean changes across multiple drivers. Enhanced experimental and modelling research to understand future changes needs to be better contextualised and evaluated against new and existing monitoring data throughout UK and international waters. Further investigation of ecosystem-based approaches in a climate change context requires a stronger emphasis on interdisciplinary frameworks that go beyond existing academic and research funding structures (Alexander *et al.*, 2018). Opportunities also exist to further capture the potential from historic monitoring and sampling programmes with regard to improved time series analysis, as for example conducted on acidification and calcification based upon comparing the HMS Challenger plankton samples from the 1870s with the present day (Fox *et al.*, 2020).

Regarding future projections, the vast majority of these have been conducted using the high emissions pathway that is consistent with the RCP8.5 climate change scenario. Although this notionally provides an upper bound on future change for use in risk assessment, it also results in an unbalanced assessment, therefore a broader range of RCPs are required in marine modelling projections.

### 3.16. Opportunities to marine species, habitats and fisheries from changing climatic conditions (N15)

- The arrival of warm water species into UK waters provides new opportunities for biodiversity and fisheries.
- The level of opportunity for this topic from changing climate conditions may increase from medium at present to potentially high in future, although there is considerable uncertainty.
- Much of the adaptation opportunity for marine species and new fisheries remains unrealised. The assessment recommends further investigation to improve information, awareness, and adaptive capacity for this topic.
- Realisation of these opportunities will also require that associated risks to the marine environment (Risk N14), including habitat availability and condition, are effectively managed.

#### Introduction

This topic assesses climate-related opportunities in the marine environment, with emphasis on ‘new’ species for UK waters as distinct from ongoing shifts in existing UK species (also recognising that such a distinction is not completely clear as changes may include re-colonisation). Its significance is related to implications for changes in biodiversity as well as ecosystem services, with the latter also covering changes to fisheries that impact on livelihoods and businesses. As with Risk N14, we are already observing major changes in the marine environment at present and expect to see greater changes in the marine environment in future. This indicates the level of opportunity may increase from medium (present) to possibly high in future, although there is considerable uncertainty, and the notion of losses and gains cannot purely be considered in objective terms. Evidence is best available currently from changes in the composition of fish stocks, but there is also some information on changing species movements. Much of this opportunity presently seems unrealised therefore ‘further investigation’ is recommended to improve information, awareness, and adaptive capacity for this topic.

It is very likely that EU-exit will have major implications, as with risk N14, most notably in terms of changes in fisheries policy (quota arrangements, regulations etc.) and the impact of any changes to international trade and markets, although final details on post-EU-exit arrangements are yet to become available. Similarly, any implications arising from the Covid-19 pandemic remain only speculative at present, although it is quite likely that some monitoring activities will have been adversely affected.

### 3.16.1 Current and future level of opportunity (N15)

#### 3.16.1.1 Current opportunity (N15)

Mean annual sea temperatures have shown a consistent warming trend since the 1970s, with coastal sea surface temperatures being 0.6°C warmer in the most recent decade compared to the 1961–1990 average (see Risk N14 for a fuller discussion of recent trends). In response to this warming, studies across a range of taxa show poleward shifts in species distributions, advancements of the breeding seasons, changes in migratory patterns, and increased abundance of warm water species while cold water species decline (Genner et al., 2017; Hastings et al., 2020). The lack of barriers to movement means that some warm-water species such as red mullet, sardines, anchovies, seahorses and squid, have been assessed as moving north at rates of up to 50 km per year, which is rather greater than equivalent land rates that are more normally considered as the yardstick for climate change dispersion (Lenoir et al., 2020).

All six of the major UK pelagic species are dependent on temperature, with those species preferring warmer waters becoming more common across the region; similarly, abundance of demersal species has been associated with warming and thermal preference (Montero-Serra, 2015). Over the last 20 years, there have been expanding fisheries for warmer water species such as seabass and red mullet and new opportunities are developing for species such as Atlantic bonito, jack, and bluefin tuna. For example, after being mainly absent for over 50 years, Northern hake as a warm-water species has recolonised the northern North Sea. Similarly, the reappearance and increased abundance of bluefin follows a similar pattern that has been explained by changing patterns of ocean and climatic variability, and in particular by the Atlantic Multidecadal Oscillation (AMO) (Faillietaz et al., 2019). Increases in abundance are also evident for many of the smaller-bodied pelagic fish species (e.g. sardine).

Abundance of some shellfish populations in UK waters have also been linked with temperature, including larval and juvenile scallop (Shephard et al. 2010). Over recent years the Mediterranean mussel *M. galloprovincialis* has been found in northern European waters, often with *M. edulis* x *M. galloprovincialis* hybrids, and although this is probably due to human agency (e.g. shipping), these new and hybrid species are likely to be increasingly favoured by warming temperatures (Mathiesen et al., 2017).

For marine mammals, opportunities are increasing for warm-water species, which observations indicate are moving northwards. These include opportunities for striped dolphin, short-beaked common dolphin, and Cuvier's beaked whale (Evans and Waggitt, 2020). As with most observed data in biodiversity, sightings of new species in new locations are a key feature of marine records, however a fuller understanding of what this means in terms of long-term shifts in species range requires further and more detailed analysis in terms of whether it is a permanent shift or due to other factors, such as changing distribution of prey species.



### 3.16.1.2 Future opportunity (N15)

Future climate projections including UKCP18 indicate continued ocean warming to 2100 and beyond, with most projections in the range 0.2°C to 0.4°C per decade. Hence, it is our inference that it is almost inevitable that there will be major changes in marine biodiversity and fisheries, providing significant opportunities for warm-water species as cold-water species are displaced, but detailed evidence for individual species in terms of expected rates of change in occurrence and abundance remains limited. Complicating factors include differential species response rates, species interactions (especially across trophic levels), and changes in socioeconomic factors such as fishing quotas and pollution loads.

The response to warming will be strongly influenced by an individual species' physiology and its thermal tolerance range, which may be further modified by phenotype acclimation (over the lifespan of the individual) and evolutionary adaptation (over multiple generations). Warming is therefore likely to enhance abundance of favoured species through physiological and life cycle effects, or indirectly by having comparatively negative effects on competitors or predators, or indirect positive effects by increasing prey species. Furthermore, in addition to warming, other climate change related influences (e.g. changes in salinity; acidification) will also impact on opportunities for different species (see Risk N14).

### 3.16.1.3 Lock in (N15)

Potentially through lack of awareness of changing opportunities and the need for biodiversity and fisheries management objectives to adjust to these rather than continuing to pursue goals based upon historic species distributions.

### 3.16.1.4 Thresholds (N15)

As noted above, species physiology and thermal tolerance is a key factor influencing opportunities and these typically have discrete temperature thresholds. For example, the CCC Thresholds project (Jones et al., 2020) explored warming-related expansion of the non-native Pacific oyster from its current range, showing considerable expansion opportunities relative to future rates of warming, although in this case 'opportunity' may be at the expense of native species through ecosystem invasion (see Risk N16).

There are also very likely to be thresholds related to the rate of change which act to restrict opportunities. A more rapid rate of change in marine temperatures and other related factors (e.g. dissolved carbon dioxide and oxygen; salinity; extreme events) may occur faster than the adaptive capacity of individual species or communities to respond to that change (e.g. for marine vegetation).

### 3.16.1.5 Cross-cutting risks and inter-dependencies (N15)

There are very important inter-relationships between healthy marine biodiversity and ecosystems, and sustainable fisheries management (see Risk N14) which require careful assessment of opportunities in order that they do not have negative consequences for other species or locations. The changing nature of pests, pathogens and invasive species (Risk N16) will also impact on both risk

and opportunity. Opportunities in fisheries will be strongly influenced by societal demand either in the UK or in other countries through global trade.

### 3.16.1.6 Implications of Net Zero (N15)

There are potential implications through the impact on fisheries and aquaculture, although presently the marine sector remains a less-developed component of the Net Zero pathway. In some cases, opportunities may increase the carbon sequestration rate for some habitats allowing a greater net contribution to Net Zero targets.

### 3.16.1.7 Inequalities (N15)

No specific implications for societal inequalities associated with climate change were identified from existing evidence in relation to opportunities for marine species, habitats or fisheries.

### 3.16.1.8 Magnitude scores (N15)

<b>Table 3.49</b> Magnitude scores for opportunities to marine species, habitats and fisheries from changing climatic conditions					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	Medium  (low confidence*)	Med-High  (low confidence)	High  (Low confidence)	High  (Low confidence)	High  (low confidence)
<b>Northern Ireland</b>	Medium  (low confidence*)	Med-High  (low confidence)	High  (Low confidence)	High  (Low confidence)	High  (low confidence)
<b>Scotland</b>	Medium  (low confidence*)	Med-High  (low confidence)	High  (Low confidence)	High  (Low confidence)	High  (low confidence)
<b>Wales</b>	Medium  (low confidence*)	Med-High  (low confidence)	High  (Low confidence)	High  (Low confidence)	High  (low confidence)

Notes: Magnitude categories based on expert judgement and assessed in terms of existing or expected impacts on biodiversity (including viable metapopulation sizes), ecosystem functioning,

and ecosystem services (including fisheries but excepting carbon storage – Risk N5). This approach is also followed because indicators based upon species numbers or habitat area are only crudely indicative of systemic relationships. We assess the magnitude as increasing from medium at present to high in the future, although with a possibly lesser increase for 2050 under the lowest climate change projections hence medium-high. Confidence is low for all these assessments due to limited evidence across the full range of species groups, although this is better for fisheries due to the wider range of observations provided by researchers and industry.

*\* Confidence would be 'medium' for fisheries only.*

### 3.16.2 The extent to which current adaptation will manage the opportunity (N15)

#### 3.16.2.1 Effects of current adaptation policy and commitments on current and future risks (N15)

The policy context for this opportunity is generally the same as Risk N14 and is discussed in more detail in that section (including variations throughout the UK). In general, there is only limited mention of initiatives specifically related to new opportunities for marine habitats and species, or for fisheries. This means that the constrained responses from non-governmental sources, either in the biodiversity or fisheries sector, is not being recognised and covered by government policies and plans. In practice, however, there are important differences between the marine biodiversity sector and fisheries sector, with government generally expected to take the lead on biodiversity issues (although with significant engagement by NGOs) whereas the latter sector is industry-led both for capture fisheries and aquaculture.

A new UK Fisheries Act 2020 to define the policy position on leaving the EU Common Fisheries Policy has now been ratified by the UK Parliament. This will determine future management of fish stocks based upon a sustainable management plans for each species, including realisation of any potential opportunities from new species. The devolved administrations are also developing post EU-exit policy arrangements. The situation is complicated because fish stocks of commercial interest are mobile and fluctuate in time across international boundaries. In the greater North Sea and Celtic Seas, nine nations operate fisheries. At present, there is no quota for new species coming into these waters such as bluefin tuna for UK vessels, whilst opportunities from some other larger-scale species movements, such as Northern hake, will require further negotiation of changing quota arrangements.

For biodiversity, the continued future conservation of Marine Protected Areas (MPAs) will be important in providing habitats where new species of high biodiversity value can become established and hence opportunities could be realised, as there is good evidence that providing habitats in good condition aids in the movement of species and their colonisation of new areas (e.g. Airolidi et al., 2008). This is especially relevant for biogenic habitats that provide large amounts of nutrients and organic matter, together with a complex and varied habitat structure, that mean they act as hotspots for biodiversity and recruitment. Nevertheless, MPAs may need to be revised, including designation of new zones, to maximise the changing opportunities for biodiversity, including expected changes in species composition and an increased likelihood of the emergence of

novel ecosystems that differ from past species assemblages and their interactions. As discussed for Risk N14, habitat condition in some MPAs is a source of concern due to multiple pressures, notably fishing and pollution sources, which also acts to constrain opportunities, although the quality of monitoring is also problematic for progress monitoring.

#### 3.16.2.2 Effects of non-Government adaptation (N15)

New species can opportunistically become established in suitable areas through natural adaptation responses but knowledge of the extent to which this is occurring at local level is limited, although evidence of large-scale movements is established. In fisheries, there is evidence of species changes in catches and in some cases the sector has adjusted to take advantage of these changing opportunities, but this is also influenced by policy (quotas etc.) and consumer demand. The limited evidence (mainly informal and anecdotal) therefore suggests to us for this assessment that an *ad hoc* rather than co-ordinated response is occurring in response to new opportunities.

#### 3.16.2.3 Barriers preventing adaptation (N15)

Regarding fisheries, some new species are unfamiliar to UK consumers compared to traditional species which may limit demand for these new species despite increased numbers and the potential for sustainable harvesting compared to traditional species (The Grocer, 2019). Consumer concerns regarding environmental sustainability are also an issue for expansion through the aquaculture sector (Black and Hughes, 2017). For biodiversity conservation, there is often limited awareness of changing opportunities and sometimes a preference for attempting to conserve the status quo or to restore to a past position (Cochrane et al., 2016). Monitoring and data collection also remain poor, with 12% of stocks being of unknown status, with notable data limitations existing for nearly all elasmobranch (shark and ray) stocks, which means for fisheries, understanding of catches is poor due to low levels of effective monitoring at sea (State of Nature Partnership, 2019).

#### 3.16.2.4 Adaptation shortfall (N15)

Despite general government commitments for sustainable seas, there is only limited mention in current policy specifically related to new opportunities for marine species in UK waters. Furthermore, the shortfall in terms of non-governmental responses, either in the biodiversity or fisheries sector, indicates that further government intervention is required to support and guide required changes in collaboration with the diverse range of marine stakeholders. It is therefore concluded that the wide range of benefits that could be provided by this opportunity in the future will not be realised in the absence of additional government intervention. However, confidence is low due to the limited evidence available.

## 3.16.2.5 Adaptation Scores (N15)

**Table 3.50** Adaptation scores for opportunities to marine species, habitats and fisheries from changing climatic conditions

Are the opportunities going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
No (Low confidence)	No (Low confidence)	No (Low confidence)	No (Low confidence)

## 3.16.3 Benefits of further adaptation action in the next five years (N15)

For marine biodiversity, there will be benefits from further investigation of new species in the context of changing species distributions, species interactions and habitat quality, especially in the context of the MPA network and therefore evidence-based recommendations for further development and enhancement of the network. As already highlighted (and also most notably for Risk N14), habitat condition is a crucial requirement to maximise new opportunities for biodiversity and current marine plans need to be further developed to recognise the key challenges for each priority habitat in the context of climate change adaptation, including their varying locations and viability as a coherent ecological network. Biogenic habitats are likely to be particularly important for realising opportunities due to their varied structure and habitat heterogeneity. These additional actions would also be consistent with further development of an ecosystems-based approach and a more systematic programme of research and monitoring that can facilitate an adaptive management approach that recognises the inevitable uncertainty and complexity in the marine environment. For fisheries, improved monitoring data would be beneficial on changing species movements and catches in order to better inform policy decisions on sustainable quotas for new species.

## 3.16.3.1 Indicative costs and benefits of additional adaptation (N15)

Many of the same options as identified for the risks to marine species and fisheries (risk N14) are also relevant for this opportunity, for realising the potential economic benefits. This includes capacity building in the industry, and the switch to an adaptive management approach for the fisheries sector, with a scale up in monitoring, scientific information and awareness raising, subsequently including this information in regular updates of fisheries policy (e.g. to set maximum catch potential for current species, include new species in policy) alongside awareness raising in the fishing sector. The CCC outcomes study (Watkiss et al., 2019) assessed that such an adaptive management strategy would have positive benefit to cost ratios, through the value of information and enhanced decisions taken. It is highlighted that there is a role for government in awareness raising for the fishing sector and for consumers, and enhanced monitoring of new species will require action by the public sector. Previous studies have also highlighted there is a need to target awareness and support in the fishing sector, to ensure opportunities are realised by small vessel operators, given their adaptive capacity will be lower (Frontier Economics, 2013).

## 3.16.3.2 Overall Urgency Scores (N15)

<b>Table 3.51</b> Urgency scores for opportunities to marine species, habitats and fisheries from changing climatic conditions				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	Further investigation	Further investigation	Further investigation	Further investigation
<b>Confidence</b>	Low	Low	Low	Low

There is a substantial likelihood that opportunities for marine species from changing climate conditions will continue to increase from present to future, although there is considerable uncertainty. However, much of the opportunity is unrealised, and there remains a significant adaptation gap according to the evidence available, particularly as there is a lack of evidence of both government-led and non-government action, unlike for some of the other opportunities in this chapter. We therefore recommend further investigation to improve information, awareness, and adaptive capacity for this topic, and hence to help structure more targeted policy responses.

Additional actions include:

- For biodiversity, further investigation is especially linked to further developing the role of marine protected areas to maximise opportunities to enhance biodiversity value (also including enhanced monitoring of species and habitat changes).
- For fisheries, opportunity assessments linked to improved data on current and projected movements of key species together with sustainable yield assessments.

## 3.16.4 Looking ahead (N15)

Improved monitoring data would be beneficial on species movements, habitat changes, and changing catches in fisheries (including shellfish) collated across all UK waters, and used to further develop model projections of future changes linked to UKCP18 and other data sources (including variables arranged according to ocean depth profile data).

## 3.17. Risks to marine species and habitats from pests, pathogens and invasive species (N16)

- There is considerable uncertainty around risks to marine species from pests, pathogens and INNS due in a large part to the scale and complexity of the marine environment.
- The risk magnitude for this topic is assessed as increasing from medium at present to high in the future, with low confidence.

- Despite current institutional risk assessment procedures providing some adaptive capacity to reduce risk, there remains an urgent need for more action to improve preparedness and address some of the key uncertainties.

## Introduction

This topic assesses pests, pathogens, and Invasive Non-Native Species (INNS; see Glossary for definitions) for the marine environment, which as highlighted previously is recognised for its high biodiversity value and its ecosystem services, including fisheries. As with Risk N14 and Risk N15, the scale and complexity of the marine environment means that considerable uncertainty remains for this risk, probably more so for pathogens. Nevertheless, based upon available evidence and drawing upon expert opinion (including horizon-scanning reports) we assess the magnitude of risk as increasing from medium (present) to high (future). The inter-connectivity of oceans and seas mean that the diffusion of pests, pathogens, and INNS is less constrained than on land, and the potential risk is considerably exacerbated by globalisation of trade and travel, particularly shipping.

The magnitude of risk increases in proportion to the degree of climate change, although the scale of this relationship is less certain, most notably due to the prospect of emerging risks especially at higher levels of climate change. The current institutional risk assessment procedures provide some adaptive capacity that can reduce this risk but there is an urgent need for more action to improve preparedness and address some of the key uncertainties. These co-ordinated actions, including through further international co-operation, should be consistent across the range of pests, pathogens, and INNS, regardless of previous policy distinctions (notions of ‘invasive species’ become rather more blurred in most marine environments, except for coastal habitats, and climate change challenges static concepts of ‘native species’).

It is very likely that EU-exit will have important implications for this risk through modified trade arrangements and associated adjustments to regulatory regimes, but details on these changes remains very limited at present. In addition, we have very limited information on how Covid-19 may modify this risk beyond a general increased public awareness of the severe consequences that arise from spread of pathogens.

### 3.17.1 Current and future level of risk (N16)

#### 3.17.1.1 Current risk (N16)

Existing evidence shows that the primary risk factor for initial establishment of harmful species and microorganisms in the UK is transport by ships, usually associated with international trade, and that the introduction of non-native species has increased in recent years (Cottier-Cook *et al.*, 2017). Climate change is therefore acting as an additional risk factor, principally through its influence on warming of seas, which can encourage establishment and spread of pests, pathogens and INNS at a magnitude not experienced previously. However, each problem species and micro-organism has its own climate sensitivity, either known or unknown (or only partly known), and it is also possible that genetic adaptation or mutation may alter that sensitivity.

In recent decades, UK shelf seas have warmed by ca. 0.1°C to 0.2°C/decade (with variations in different biogeographic zones), including stronger warming episodes during particular periods or years (e.g., 2014 – see Risk N14 for a more detailed discussion of recent warming trends). Our assessment is that incremental warming therefore provides increasing scope for establishment and spread of problem species and pathogens that are damaging to native biodiversity. Other climate-related factors, notably changes in salinity, may also be contributed to the risks, together with non-climate related stresses such as pollutant loads, turbidity, and ocean acidification.

This threat to biodiversity is evidenced by reports of increasing problems with INNS and pathogens including from viruses, fungi and bacteria. For example, fish gill disease is a notable problem for aquaculture, and this can occur from parasite, virus, or bacterial sources, with elevated temperatures and high salinity noted as exacerbating risk factors (Boerlage *et al.*, 2020). Increasing risks from problem species and pathogens have also been identified through their importance for human health protection (e.g., *Vibrio* bacteria in shellfish) and threats to commercially important marine species, especially bivalve shellfish (e.g., oysters) (Danovaro *et al.*, 2011; Bresnan *et al.*, 2020).

An investigation of eight target INNS in England and Wales showed 209 records of one or more of these species in MPAs, and that three of the INNS (*Undaria pinnatifida*, *Sargassum muticum*, and *Corella eumyota*) had led to changes in community composition (Macleod *et al.*, 2016). Evidence also suggested potential changes in community structure could impact upon on some MPA intertidal and subtidal biogenic features, including reefs, subtidal macrophyte-dominated sediment, seagrass beds and native oysters. A matrix tool using a 'traffic light' system based on MPAs features, identifying those susceptible to (or already colonised by), defined 16 of the 112 MPAs as higher risk (i.e., 'red'), in that they contained five or more suitable features and environmental conditions for the establishment by one or more of the eight INNS.

Major pathways for the arrival of invasive non-native species (INNS) in UK waters are on the hulls of ships, through the release of ship ballast water, from aquaculture-related introductions, and as stowaways on fishing or other mobile equipment. Shipping represents the main transport mode for world trade and with increased globalisation the scale of shipping transport has further increased in recent decades. For these reasons, the level of risk is increasing. Ports typically become the initial focal areas for introduction of INNS but they can also become established at less obvious locations: for example, one notable INNS, the gulf wedge clam, was recently discovered at a remote site in Lincolnshire (Willing, 2015). Although not known for certain, the cause of the introduction of Pacific oyster on the east coast of Scotland has been proposed to be from ballast water, as there had been no aquaculture ventures for the species in that region (Smith *et al.*, 2014). Once established, problem species usually become very difficult to eradicate in the marine environment, and hence can be even more problematic than terrestrial or freshwater INNS. For this reason, prevention is an even more important strategy.

There are also some indications that the increased presence of artificial structures in the marine environment, including platforms for offshore wind farms, or artificial reefs, may be associated with increased colonisation by non-native species due to the different substrates (e.g., Herbert *et al.*,



2017, Coolen *et al.*, 2020). At present, however, the evidence is not yet conclusive whether this is increasing the risk from damaging invasive species.

In addition to observation records of problem species already present in the UK, horizon scanning provides a valuable tool to consider new INNS that may arrive both at present and in the future. Following such a methodology and including a risk assessment based upon scale of potential invasiveness (i.e., disruption to native ecosystems), a previous exercise found that eight marine species are included in a list of the top 30 most invasive species in Great Britain (Roy *et al.*, 2014a). These include Asian shore crab, brush-clawed shore crab, American comb jelly, veined rapa whelk, cauliflower sponge, rough agar weed, American lobster, and Japanese sting wrinkle (the latter two species being highlighted on Defra's priority eradication list).

More recently, an expert-based horizon scan of invasive alien species has been completed for the island of Ireland (Lucy *et al.*, 2020), finding that crustacean species (freshwater and marine) were the taxa most commonly identified as a threat due to their multiple pathways of introduction, their ability to act as ecosystem engineers and their resulting high impacts on biodiversity. The most likely marine invader was identified as warm-water barnacle (*Hesperibalanus fallax*), with pom-pom weed (*Caulacanthus okamurae*), American razor-clam (*Ensis leei*), Brush-clawed shore crab (*Hemigrapsus takanoi*), the sponge *Celtodoryx ciocalyptoides*, and Asian shore crab (*Hemigrapsus sanguineus*) also identified in the top 40 overall threats. Some of these INNS have already been recorded in south west England and Wales, therefore the risk of spread to Northern Ireland is high and they are highlighted as clear 'door-knocker' threats. Similar horizon scanning assessments of risk on a 10-year timescale have also been conducted for the EU, including the Atlantic biogeographic region where the UK is located (Roy *et al.*, 2019; Tsiamis *et al.*, 2020).

Diseases are not uncommon in the marine environment and may impact marine ecosystems by influencing community structures, age distributions, trophic interactions, hydrodynamics, and biotic structures. The relationship between climate change and pathogens is less well understood compared to existing pest species and INNS and may also be occurring through indirect rather than direct climate-related factors, as, for example, through changing host-pathogen relationships (Harvell *et al.*, 2009).

Climate-related range shifts may therefore occur in both hosts and pathogens which therefore requires a multi-factorial risk assessment, identifying the possibility for major unknowns and emergent risks. For example, the spread of some viruses may be associated with the movement of host animals due to the changing opportunities provided by ocean warming. This may include the morbillivirus group of pathogens, amongst which the Phocine morbillivirus (phocine distemper virus: PDV) has been prominent in causing recent seal deaths in European waters, particularly in Denmark (Duignan *et al.*, 2014). Other mammals can be infected by similar viruses, include dolphins and otters, therefore the consequences for marine biodiversity from a large-scale outbreak may be high where mixing of different animal communities is more common. Attribution of such outbreaks to climate change is extremely difficult due to the variety of possible cause-effect relations. It is possible that warming may have accelerated development of the pathogen. Alternatively, shifts in land-use or rainfall patterns can increase terrestrial pathogen flow to the coastal zone, increasing marine mammal exposure.

Viral infections are also known to affect other taxa, including Atlantic salmon. However, by comparison to farmed species, the impacts of diseases on wild marine fishes are extremely difficult to enumerate, owing largely to the challenges of studying highly mobile organisms in open seas where direct observation is less feasible unless through limited sampling or liaison with the fishing industry.

Climate change may also act to decrease some pathogens, although again evidence is very limited. In reviewing disease incidence across a range of taxa, Tracy *et al.* (2019) noted decreasing reports of incidence for fishes, but as these have incurred human-induced population declines and reduced population densities this may be acting to reduce disease rather than warming seas.

### 3.17.1.2 Future risk (N16)

The scientific consensus is that risks from pests, pathogens and INNS will increase in proportion to the degree of future additional marine warming but there is considerable uncertainty on how this will occur (e.g., Donovaro *et al.*, 2011; Burge *et al.*, 2014; Mellin *et al.*, 2016; Rinde *et al.*, 2017). Warming of UK shelf seas is projected to continue to 2100 and beyond with most projections simulating increases of between 0.25°C and 0.4°C per decade, but with regional biogeographic differences and the greatest warming in the Channel and southern North Sea (see Risk N14).

In addition, several of the other stressors identified above are likely to continue (as discussed in more detail for Risk N14), including ocean acidification and changes in salinity levels due to stratification and modification of currents, increasing the vulnerability of marine organisms to invasive species or pathogens. Furthermore, at higher magnitudes of climate change there is an increasing possibility of emergent unknown risks as existing marine ecosystems are increasingly disrupted and dispersed to produce new biotic interactions and novel ecosystems.

Socioeconomic risk factors will also strongly influence the magnitude of risk, including future changes in global trade patterns, ocean pollution, and further expansion of aquaculture. Regarding trade patterns, increased shipping from regions such as SE Asia, Africa and South America is likely to further increase exposure to new problem species and pathogens. The key issue will then be the degree of refinement and enforcement of biosecurity procedures, especially at the most vulnerable locations such as ports and harbours.

Information on the changing pattern of risk is primarily available for problem species and pathogens that are already prominent in the UK or Europe, such as the Pacific oyster. In addition to those INNS identified above, other known problem species that could further spread in the UK include Chinese mitten crab, which has a lifecycle that shifts between marine and freshwater environments, and the carpet sea squirt.

Regarding Pacific oyster, this is an introduced species that has already become established on the Channel coast aided by warming waters in recent decades, with sporadic colonisations established elsewhere in the UK, including as far north as the Firth of Forth (Scotland: Smith *et al.*, 2014). A

continuing trend towards warmer seas mean it is likely to become successfully recruited on an annual basis in south-west England, Wales and Northern Ireland by 2040 (Rinde *et al.*, 2017; see also 'Thresholds' section below). This has important implications for biodiversity because as an 'ecosystem engineer', the Pacific oyster can transform intertidal systems resulting in a more homogeneous habitat impacting especially on native bivalves such as mussels, cockles and the native oyster, in addition to blue mussel aquaculture locations (Jones *et al.*, 2020). Negative impacts may also extend to intertidal bird species such as Dunlin, red knot, common gull and oystercatcher which use mussels as a food source (Waser *et al.*, 2016). Conversely, there may be some potential benefits such as for improving water quality, wave attenuation for flood defence, and an additional food supply, although the actual trade-offs between benefits and losses will depend on the density of colonies and local site factors (Herbert *et al.*, 2016).

Regarding pathogens, there are many unknowns, notably changing host-pathogen relationships, range shifts (hosts and pathogens), and increasing disease frequency and virulence due to increasing thermal stress on host species and climate-change related suppression of host immune responses (Burge *et al.*, 2014). In addition, there is limited data for most biodiversity-related pathogens which constrains modelling of future patterns of change.

A further concern regarding aquaculture, which is planned to further expand in the UK (Black and Hughes, 2017), is the impact of antimicrobial resistance (AMR) because antibiotics are commonly used in feedstuff to control bacterial infections. Meta-analysis across several countries (including the UK) has shown an association between aquaculture-related AMR and climate warming: the causes of this relationship are poorly understood but likely to involve the increased virulence of pathogens at higher temperatures and associated increased use of antimicrobials to protect against fish mortality, hence the rise in AMR (Reverter *et al.*, 2020).

#### 3.17.1.3 Lock-in (N16)

There are potential lock-in risks associated with continuing to develop international trade without a full assessment of the changing distribution and consequences from INNS and pathogens. Once a problem species is established in the UK, eradication often becomes extremely difficult (more especially in marine environments, as noted above), hence the initial introduction (either deliberate or inadvertent) can result in a form of lock-in whereby the natural ecosystem is potentially irreversibly modified with potential consequent effects on biodiversity, ecosystem functioning and ecosystem services, and for ecosystem-based adaptation. This potential for irreversibility may be increased with warmer seas and therefore for the risk to become locked in for the future.

#### 3.17.1.4 Thresholds (N16)

Climate thresholds are important in establishment of INNS and likely to be also key factors in the virulence of pathogens and in host-pathogen relationships, especially for sea temperature and also salinity. The relationship of threshold effects with species physiology has been identified as a key issue for further research (Monaco and Helming, 2011). The CCC thresholds project (Jones *et al.*, 2020) investigated temperature thresholds for establishment and spread of the Pacific oyster as a case example (using a threshold for spawning of 825 degree-days for a daily mean bottom

temperature of 10.55 °C). This analysis showed a potential for range expansion across much of the UK by the 2080s as temperatures increase, in some locations potentially threatening native oysters, with the rate of change depending on climate change projection. Greatest gains in suitable area were observed in England, which was driven predominantly by large areas of the shallow North Sea around Dogger Bank becoming suitable. Scotland saw the largest percentage increase in suitable area, driven by large increases in suitable habitat in the Inner Hebrides. As noted above this is an example where expansion may be perceived as an opportunity by one sector (shellfish aquaculture) and a risk by another sector (biodiversity), in addition to having regional implications in terms of whether the invasive species is already established.

#### 3.17.1.5 Cross-cutting risks and interdependencies (N16)

In addition to biodiversity there are important interactions with fisheries (including aquaculture) and with human health, livelihoods, and well-being. As noted above regarding the Pacific oyster, INNS can also potentially involve some benefits through enhancement of some ecosystem services but there are often difficult trade-offs against native biodiversity and these trade-offs may also vary with location. The spread of pests can also have important implications for marine heritage, as exemplified by increased problems reported with the impact of shipworm (Harkin *et al.*, 2020).

The risk of pests, pathogens and INNS may be increased due to pressures on native biodiversity that both reduce the competition that problem species will experience, hence facilitating their spread, and also make native biodiversity more susceptible to pathogens such as through weakened immune system responses. In addition, it will be important that the risk of pests, pathogens and INNS are included in habitat enhancement, recovery, restoration and creation projects, and associated plans for an expansion in nature-based solutions. For example, native oyster restoration, seagrass restoration and saltmarsh creation and other similar schemes (as discussed in Risks N14 and N17), which also require re-introduction of native species (either sourced from the wild or from hatcheries/farms), will also require increased awareness of the inherent risks from the spread of parasites, pathogens and INNS as guided by codes for best practice in licensing obligations (e.g., in Scotland, the Scottish Code for Conservation Translocations: National Species Reintroduction Forum 2014).

It is also possible that increased runoff and discharge of pollutants from land (both point sources such as sewerage systems and diffuse sources as from agriculture) due to heavier rainfall events could increase risk from pathogens, as is occurring with excess nutrient runoff and Harmful Algal Blooms in coastal waters (Bresnan *et al.*, 2020). In addition to biodiversity impacts this can have adverse impacts for fisheries, especially for shellfish.

#### 3.17.1.6 Implications of Net Zero (N16)

There are potential implications through the impact on key species and habitats that deliver carbon sequestration benefits ('Blue Carbon'), although very little evidence is available. In addition, there may be indirect effects through impacts on fisheries and aquaculture, both of which are seen as

low-carbon food sources compared to some other alternatives. However, presently the marine sector remains a less-developed component of the Net Zero scenario.

In the context of plans for further expansion of renewable energy, as also noted above there is some evidence to suggest that the platforms used for new offshore wind farms may be preferentially colonised by non-native species due to the different substrates in the platforms. Although evidence is currently limited, the risk is that platforms act as ‘stepping stones’ for expansion of these non-native species.

### 3.17.1.7 Inequalities (N16)

No specific societal inequalities associated with climate change were identified in relation to risks marine species.

### 3.17.1.8 Magnitude scores (N16)

<b>Table 3.52</b> Magnitude scores for risks to marine species and habitats from pests, pathogens and invasive species					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	Medium  (medium confidence*)	High  (low confidence)	High  (low confidence)	High  (low confidence)	High  (Low confidence)
<b>Northern Ireland</b>	Medium  (medium confidence*)	High  (low confidence)	High  (low confidence)	High  (low confidence)	High  (Low confidence)
<b>Scotland</b>	Medium  (medium confidence*)	High  (low confidence)	High  (low confidence)	High  (low confidence)	High  (Low confidence)
<b>Wales</b>	Medium  (medium confidence*)	High  (low confidence)	High  (low confidence)	High  (low confidence)	High  (Low confidence)

Notes: Magnitude categories based on expert judgement and assessed in terms of existing or expected impacts on biodiversity (including viable metapopulation sizes), ecosystem functioning, and ecosystem services (including fisheries but excepting carbon storage – Risk N5). This approach is also followed because indicators based upon species numbers or habitat area are only crudely indicative of systemic risks. Risk magnitude is assessed to increase from medium at present to high

in the future under all climate projections due to the high climate sensitivity of marine organisms and micro-organisms associated with this risk. Confidence is medium for present risk but low for the future because the full scale of this risk remains to be established and there is an increased prospect of new emergent risks.

*\* Confidence is low for pathogens.*

### 3.17.2 Extent to which current adaptation will manage the risk (N16)

#### 3.17.2.1 Effects of current adaptation policy and commitments on current and future risks (N16)

##### 3.17.2.1.1 – UK wide

The risk topic is owned by Defra, the Scottish Government, Welsh Government and DAERA. The general policy context for management of pests, pathogens, and INNS is provided in Risk N2, including relationships with international agreements (Bern Convention etc.) and other larger-scale international initiatives. Strategies to control and eradicate INNS were also a commitment made by the UK Government to the 2020 UN Aichi Targets for Biodiversity.

In addition to these general requirements, the marine environment also requires more specific aspects of risk management in relation to climate change adaptation. The general marine policy context is covered in Risk N14. Regarding this specific risk, the interconnectivity of the marine environment means that prevention is the most effective control strategy as measures to control spread once established can be very difficult to implement effectively in marine waters, especially for INNS.

The Great Britain INNS strategy covers marine environments but does not include non-native genetically modified organisms, bacteria or viruses, nor animal or plant diseases (which are included in the UK Biological Security Strategy), although it does include invasive species that carry disease. The GB Non-native Species Secretariat conducts risk assessments, and monitors incidents and outbreaks. Risk assessments are now being further developed through horizon scanning of future risks based upon changes in trading relationships.

In May 2019, the UK Government published its comprehensive pathway analysis (as required then by EU Regulations) which identified three priority pathways for controlling INNS in the marine environment: (i) hull fouling, (ii) ballast water, and (iii) contaminants of aquaculture animals. Further measures to provide increased prevention have been identified including: (i) ensuring vessels arriving or leaving UK waters have stringent hull cleaning and (ii) all ships to have a ballast water management plan. The UK Government is committed to, but yet to ratify, the International Convention for the Control and Management of Ships' Ballast Water and Sediments ('Ballast Water Management Convention') as associated with the increasing threat of invasive species. Ratification was expected during 2020 but was delayed due to the Covid-19 pandemic (on the grounds that the priority was to maintain the flow of essential goods) and is therefore now expected to follow a process of consultation and ratification once the Covid-19 crisis has been resolved (Maritime & Coastguard Agency, 2021).

#### 3.17.2.1.2 England

The second National Adaptation Programme and the 25YEP for England make related commitments to continue with the GB INNS Strategy and to review it in the context of climate change but no detailed actions are provided for the marine environment beyond a continuation of these existing policies.

#### 3.17.2.1.3 Northern Ireland

Northern Ireland collaborates with the Irish Republic on an all-Ireland approach to INNS, which includes the threat from marine species. There are also plans for further integration of Northern Ireland into a UK Non-native Species Secretariat. The 'Invasive Alien Species Strategy for Northern Ireland' aims to address knowledge and awareness gaps, and minimise introductions and spread of INNS, whilst also aiming to eradicate and control existing problem species, also through a partnership and capacity building approach. The Marine Plan for Northern Ireland (2018), which could also provide a strategic pathway to build adaptive capacity for this risk, is yet to be adopted by government.

#### 3.17.2.1.4 Scotland

The second Scottish Climate Change Adaptation Programme (SCCAP2) identifies a similar continuation of existing commitments and that Marine Scotland will continue to keep under review how it approaches INNS management, including partnership working to minimise the threats posed by INNS. The Marine Plan for Scotland also establishes a general policy framework for these actions linking with biodiversity, fisheries and other sectors. The SCCAP2 also notes a new potential indicator for the future to record absence of INNS as complement to the current indicator on presence of INNS.

#### 3.17.2.1.5 Wales

In Wales, the latest Adaptation Plan also makes a commitment to further monitoring and planning for marine INNS, including the INNS Portal which was launched as part of the National Biodiversity Network (NBN) Atlas Wales in November 2018. The Welsh National Marine Plan (2019) defines general marine policy guidance for the next 20 years. This includes plan policies that support Good Environmental Status through the management of marine INNS, requiring that proposals should demonstrate how they avoid or minimise the risk of introducing and spreading INNS. Although not directly targeting climate risk as the cause of INNS, the Welsh National Marine Plan does state the support of climate change adaptation and resilience as one of its 13 main objectives.

#### 3.17.2.2 Effects of non-Government adaptation (N16)

The responsibility to report and manage incidents remains with the landowner, which depends on the awareness, knowledge and capacity of an individual or organisation, and therefore can be rather variable, without further specialist support. Similarly, ship owners and crew have variable knowledge of the risks and therefore do not always manage them according to best practice (e.g., ballast water release).

Partnership working and knowledge exchange to increase awareness of risks is promoted and supported. For example, the Wales Invasive Non-native Species Group, WaREN, was formed to help identify INNS priorities and resolve issues relevant to Wales.

### 3.17.2.3. Barriers preventing adaptation (N16)

Changes in the distribution of pests, pathogens, and INNS can be rapid and unexpected, linked not only to climate factors, but also changes in globalisation, especially shipping routes. Therefore, awareness of the changing risks and capacity to respond quickly are crucial, although this often remains under-developed (Giakoumi et al., 2019). Further work on the disbenefits and benefits from different non-native species (including those defined as INNS) is also required to achieve a consistent position; in some cases, the non-native species may have advantages for commercial extraction or habitat restoration that need to be balanced against disbenefits through a structured risk assessment and options appraisal (Giakoumi et al., 2019). A notable example, as described above, would be conflicting attitudes towards the spread and establishment of Pacific oyster in the UK, including as a threat to native oyster populations. Port and harbour authorities (including marinas) are key organisations together with informal public networks (local angling networks, fishing operators, divers etc.). In addition, the role of local government can be crucial, although resources are not always available to cover this role, and therefore response capacity can be quite variable.

It should also be emphasised that although some established pest species are already well known, the occurrence of INNS and pathogens has a strong stochastic and therefore emergent risk component, meaning that there are limits to forecasting and prediction, even with enhanced horizon-scanning capability. With regard to climate change, a challenge for knowledge exchange and improved awareness is that the role of climate factors is not fully understood, especially for pathogens. This additional element of unpredictability, although it can be partly addressed by improved international collaboration and data sharing on changing risk parameters, effectively requires a multi-tiered approach to contingency planning, including through scenario exercises, so that even for 'surprise' introductions there is a protocol for control and containment.

### 3.17.2.4 Adaptation shortfall (N16)

In summary, our view is that the main emphasis of these policy commitments is on continuation of existing policies and there is little extra detail regarding the additional risks from climate change and specifically for the marine environment, although references are starting to be made in key documents. In addition, it is not yet clear how plans for continued international collaboration (including with the EU) will be taken forward following EU-exit, including for surveillance, monitoring and horizon scanning.

While there is some evidence of non-government actions, addressing this risk requires specialist support and guidance, more especially to identify and communicate new and emerging risk species and micro-organisms. This is a topic that requires a co-ordinated approach, linking science and policy, and with the capacity to anticipate and regularly update the changing nature of the threats.



Based on this, current adaptation is assessed as insufficient to manage future risks down to a low level. We also note that due to evidence constraints that confidence is low, especially as evidence on the effectiveness of adaptation options remains rather limited.

### 3.17.2.5 Adaptation Scores (N16)

<b>Table 3.53</b> Adaptation scores for risks to marine species and habitats from pests, pathogens and invasive species			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

### 3.17.3 Benefits of further adaptation action in the next five years (N16)

As identified above, pest species and INNS, once established, are very difficult and costly to eradicate in the marine environment. Similarly, for marine pathogens, land-based management methods that are currently employed of quarantining, culling, or vaccinating are not successful. This means that enhanced control measures through biosecurity regulations and best practice have the greatest benefits in reducing risk, complemented by improved forecasting of outbreaks to provide additional focus. Forecasting is also associated with requirements for strong systems of international monitoring and surveillance to provide updated data on problem species and pathogens. Improved data and forecasting capability would also allow further investigation of the role of climate-related parameters in risk assessment. Enhanced prevention through policy co-ordination will also be crucial, notably further steps to embed biosecurity in national and regional marine planning in relation to climate change, and also stronger incorporation of biosecurity planning as part of the consenting process for relevant marine sectors.

At a more local level, there are very likely to be benefits from enhanced engagement and knowledge exchange with community groups and practitioners. For example, NRW have developed collaboration with the Welsh Fishermen's Organisation to record INNS.

#### 3.17.3.1 Indicative costs and benefits of additional adaptation (N16)

There is some information on control (adaptation) costs, which can be considered either an impact or reactive adaptation. These can involve high costs. For example, the Carpet Sea Squirt has spread to the UK and there have been a number of recent outbreaks in ports. Williams et al (2010) estimated the cost of eradication of the UK population from currently affected marinas at £2.4 million, but if this species spreads UK-wide, the overall cost of eradication could rise to £72 million. Hence, the total eradication cost would be very much higher. It should also be noted that these are cost-based measures so do not capture people's willingness to pay to avoid marine INNS. More generally, this indicates that once established, managing invasives can be costly. Given that these may spread as a result of climate change, and the need for co-ordinated provision of information,

there would seem to be a case for an expanded role for Government intervention to provide enhanced monitoring and surveillance and early response. Evidence on the economic justification for such a scale up is available for terrestrial invasives and suggests high benefit to cost ratios (Moran et al., 2013) and it is assumed similar ratios would be applicable for the marine environment.

### 3.17.3.2 Overall urgency scores (N16)

<b>Table 3.54</b> Urgency scores for risks to marine species and habitats from pests, pathogens and invasive species				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Low	Low	Low	Low

Given the projected increase in risk magnitude for this topic (from medium at present to high in the future across the UK), together with the lack of sufficient recognition of climate change in current policy frameworks and risk assessment procedures, a 'More Action Needed' urgency score has been assigned to this topic. The scale and complexity of the marine environment means that considerable uncertainty remains for this risk, indicating that a twin-track approach of improved contingency-based risk management measures and further research to address key knowledge gaps would likely to be most useful. As part of this enhanced capability, the use of scenario planning, guided both by evolving knowledge and additional 'what-if' scenarios, would have added value in enhancing knowledge exchange between science, policy, and practitioners.

Actions include:

- Collect long-term data to better understand host-pathogen interactions, and how outbreaks and disease syndromes are affected by extreme events, climate variability, and climate change.
- Improve surveillance, horizon scanning, and modelling capability for INNS and pathogens, including through international collaboration.
- Improve biosecurity awareness and promotion of best practice across all relevant sectors including in habitat enhancement, recovery, restoration and creation.
- Enhanced emphasis on prevention measures as crucial for marine INNS, including implementing pathway action plans for priority pathways identified through risk assessments.
- Improve public awareness, including further use of citizen science.
- Improve understanding of factors that contribute to disease-resistant organisms.
- Improved understanding and contingency planning for emergent risks, especially for novel pathogens.

#### **3.17.4 Looking ahead (N16)**

As above, the next CCRA would benefit from improved large-scale data on the dynamics of marine INNS and pathogens, complemented by scenario modelling capability to further test and investigate the evolving interaction of climate change relationships with non-climate risk factors (international policy, trade, demographics etc.).

### **3.18 Risks and opportunities to coastal species and habitats due to coastal flooding, erosion, and climate factors (Risk N17)**

- The magnitude of risk to coastal species and habitats from changing climatic conditions is projected to increase from medium at present to high in the future. This will be especially influenced by the rate and magnitude of sea level rise, which more recent projections including UKCP18 suggest may be higher than assumed for CCRA2.
- Although negative risks predominate, there are also opportunities for habitat creation and species gains depending on habitat type, location, magnitude of climate change and sea-level rise, and management response.
- Overall progress on managing this risk remains limited, although there are increasing numbers of positive local examples that can be highlighted. Nevertheless, significant barriers remain and for much of the coast there is an increased risk of lock-in to an unsustainable future.
- Evidence indicates that adaptation through effective implementation of nature-based solutions, including managed realignment and habitat restoration, can reduce the risks and provide multiple benefits and potential opportunities.
- Adaptation strategies need to be designed to be more flexible and robust against the wider range of climate change projections, and especially for higher rates and magnitudes of sea-level rise.

#### **Introduction**

Coastal habitats occur at the terrestrial/marine interface including both intertidal and supratidal environments, notably saltmarsh, machair, vegetated shingle, sand dunes, saline lagoons, and sea cliffs. As an island nation, the UK is internationally recognised for its coastal habitats and species, and these provide a major contribution to national identity. In addition to their biodiversity value, these habitats provide many ecosystem services, such as flood and erosion protection, fisheries (especially as nursery areas), climate regulation (through carbon storage), tourism and leisure opportunities, and through interaction of the natural environment with cultural heritage. The UK National Ecosystem Assessment cited one study (COREPOINT, 2007) that assessed the total value of coastal ecosystem services as worth at least £48 billion, whilst the Office for National Statistics (2016) prototype methodology for ecosystem accounts provided an indicative net present value over 50 years of £22.7 billion based upon those services that are more easily quantified.

Although policy may define the issues separately (as suggested by the initial nominated list of risks for CCRA3), this assessment covers both coastal erosion and flooding together. By doing so, we

recognise that these are inter-related and co-evolving processes, and that changes in one type of hazard can affect the other and the resultant risks. Erosional processes modify coastal morphology and therefore flood risk. For example, this can lead to a breach in a shingle or sand barrier, or loss of a beach or saltmarsh, which can lead to flooding. Similarly, from an alongshore perspective, changing patterns of erosion or accretion may exacerbate or reduce flood risk down-coast. High water levels that cause flooding can also significantly alter patterns of erosion through changes in hydrodynamic forcing with potential threshold effects. Assessing risks from erosion and flooding together is therefore consistent with moves towards developing an integrated systems approach for adaptive risk management (Dawson *et al.*, 2015; Pollard *et al.*, 2019).

Although the dominant effect of climate change may be negative, we also recognise there may also be positive aspects for some habitats and species, especially when erosion is accompanied by accretion and habitat creation in other locations, highlighting the importance of integrated coastal zone management. In the context of biodiversity, it is also necessary to consider other climate-related changes in coastal areas, notably changes in temperature and precipitation, and potentially wind, which may increase the vulnerability of some habitats and species.

We assess this risk as increasing from medium (present) to high in future, this being especially influenced by the rate and magnitude of sea level rise (which the most recent assessments indicate may be at a higher rate/magnitude than assumed for CCRA2 – see Chapter 1: Slingo, 2021). At present adaptation responses are inadequate to match the scale of the risk nor to realise potential opportunities for habitat creation, and we also recognise significant lock-in risks. Therefore, as with CCRA2, this topic remains a priority for more policy action.

Our assessment of risk magnitude is supported by good evidence on the scale of present-day impacts and by using modelling and extrapolation of present risk to infer future changes which increase in proportion to climate-change related drivers, notably sea-level rise. Evidence of the effectiveness of current adaptation in moderating the risk is more limited, although often available by default through present-day residual impacts which show a significant adaptation shortfall. Nevertheless, there is also available evidence that adaptation options such as managed realignment and habitat restoration, if implemented appropriately for the location, can have a key role in reducing the risks and providing multiple benefits and potential opportunities, although more research and evidence is also required here to better support adaptive management in practice. The existing level of implementation of managed realignment and habitat restoration is insufficient even at present rates of sea-level rise, and very small considering historic losses. Further action and supporting research are also required on the implementation of more strategic risk management approaches that integrate realignment or rollback options with structural defences that will inevitably continue to be required at some locations, but which also have an impact on the adjacent coastline. With appropriate support, Shoreline Management Plans can provide an ongoing science-policy mechanism for taking forward adaptive management solutions, including further appraisal of different adaptation pathways based on alternative climate change scenarios.

Both EU-exit and Covid-19 are very likely to further influence climate change risks, most notably in terms of indirect effects such as delays to adaptation actions and progress monitoring, but at present we have no evidence for this.

### 3.18.1 Current and future level of risk or opportunity (N17)

#### 3.18.1.1 Current risk (N17)

##### 3.18.1.1.1 Sea-level rise and other Climate-related factors

As highlighted in Chapter 1 (Slingo, 2021), evidence suggests an acceleration in sea-level rise over recent decades (global mean acceleration  $\sim 0.1 \text{ mm/yr}^2$ : Veng and Andersen, 2020) such that the trend in absolute mean sea level 1993-2019 for the UK coastline based on satellite data is now generally 2.0-2.5 mm/yr (slightly higher to the north and east). Local patterns of sea level rise relative to the land (as measured by tide gauge data) are also influenced by distinctive local and regional secular effects, in addition to land movements (generally subsidence in the south or uplift in the north). These variations complicate an overall assessment of risk, but the general pattern is for an increased rate of relative sea-level rise throughout the UK coastline (at least 2-3 mm/yr), which is acting to further increase the flood risk for low-lying habitats and their dependent species. In addition, as reported in previous CCRAs, estuaries and other local coastal features can have their own patterns of faster and slower water level rises due to phenomena such as amplification of the 18.6-year lunar cycle, or due to local fluvial, morphodynamic and hydrodynamic interactions (Wang and Townend, 2012; Robins *et al.*, 2015).

There is also evidence for an increase in North Atlantic storms at the end of the 20th Century, linked to concurrent changes towards a more frequent positive winter NAO, and this can be particularly important factor for erosion risk, depending on location. Using a 69-year numerical weather and wave hindcast, Castelle *et al.* (2018) found significant increases in NE Atlantic winter-mean wave height, variability, and periodicity, also showing strong correlations with the NAO index. Similarly, review of an array of evidence sources by Wolf *et al.* (2020) also identified an apparent trend towards both increased storminess and increased wave heights in the NE Atlantic, although also noting considerable interannual and interdecadal variations.

##### 3.18.1.1.2 Coastal Erosion and Accretion

Previous CCRAs have synthesised evidence that a significant proportion of the coastline of the UK is currently suffering from erosion; for example, one estimate placed this proportion at 17% (EUROSION, 2004). In England and Wales, 28% of the coast has been identified as experiencing erosion  $>10 \text{ cm}$  per year (Burgess *et al.*, 2007). The National Coastal Erosion Risk Mapping Project (NCERM: Rogers *et al.*, 2008) found that 42% of England and Wales is at risk from coastal cliff erosion, of which 82% is undefended. When including coastal floodplains, beaches, barriers, and intertidal areas, including areas protected by artificial defences, the proportion at risk increases to 68% (FutureCoast, 2002). Over the longer term, investigation of chalk cliff erosion in southern England has shown an increased erosion rate in recent centuries, which is attributed to reduced sediment supply and thinning of beaches (Hurst *et al.*, 2016). Assessment of coastal SSSIs in England assumed to be at risk from erosion from the present up to 2025, based upon extrapolation of historic erosion rates using NCERM data, produced a central estimate of 600ha (50% likelihood) and an upper range estimate to 800ha (5% likelihood).

In Scotland, 78% of the coast is considered 'hard or mixed' (i.e., with low erosion rates), 19% is 'soft/erodible', whilst 3% has artificial defences (Hansom *et al.*, 2017). As noted by previous CCRAs, evidence shows that the notion that postglacial isostatic land uplift in northern Britain would mean that coastal impacts associated with eustatic sea-level rise would be a lesser risk factor for Scotland (and Northern Ireland) is not tenable, and relative sea level rise is now dominant throughout the UK. The Dynamic Coast project has affirmed the implications of this changing hazard by using shifts in the mapped position of the MHWS (Mean High Water at Spring Tides) line, finding that, since the 1970s, 77% of the soft/erodible coast in Scotland has remained stable, 11% has accreted seawards and 12% has eroded landwards (Hansom *et al.*, 2017). Using a longer time interval, comparisons of the post-1970s period with the late 19<sup>th</sup> century suggest a reduced extent of accretion (by 22%) in Scotland, a 39% increase in the extent of erosion, and a doubling of average erosion rates from 0.5 to 1.0 m/yr (and similarly, average accretion rates have almost doubled to 1.5 m/yr). The larger shifts in the balance of erosion and accretion are found particularly in the east coast and Solway Firth area, although some localised areas on the west coast can also be distinguished, notably for the Western Isles, which are important for their distinctive machair habitats.

For Northern Ireland, there is generally less detailed information on coastal change. However, it has been estimated that ca. 20-30% of the coastline is either eroding or at risk of erosion (EUROSION, 2004; McKibben, 2016), and that 32% of the coast has some form of protection (Cooper *et al.*, 2016).

Erosion has had both direct effects on exposed undefended coastlines and indirect effects when associated with hard defences. In the latter case, as highlighted in past CCRAs, the indirect effect has been 'coastal squeeze' whereby erosional impacts have been concentrated on the intertidal zone to seaward of defences causing habitat loss. Around 72% of the intertidal flats and marshes in England are considered at risk of coastal squeeze because of the presence of landward sea defences, whilst in Wales, 44% of the coastal Natural 2000 sites have been flagged as being at risk from coastal squeeze (Miles and Richardson, 2018); no equivalent indicators for coastal squeeze are yet available for Scotland and Northern Ireland. CCRA2 also noted the severe effects of erosion that have occurred during severe stormy periods, such as winter 2013/2014, which can have a long-term legacy in terms of habitat loss.

Another less-reported type of coastal squeeze is occurring in those cliff-top locations that have distinctive maritime grasslands of high biodiversity value. These grasslands are often bordered inland by agricultural land and whilst the farmland boundary has tended to remain in the same local position, erosion of the cliffs has acted to reduce the area of maritime grassland habitat, although no national-level figures are currently available for the extent of this loss.

Areas of accretion which represent habitat creation opportunities are more localised but include ness features and accretion associated with sediment sinks in estuaries (e.g., The Wash; Humber estuary; Firth of Tay; Dee estuary). Currently most of the coast has a constrained sediment budget because of the high proportion that is defended, although, as noted above, the evidence does also suggest that unprotected areas (e.g., soft cliffs) may be experiencing increased erosion rates. The recycling of eroded sediments to supply accretion zones is complicated by local and regional tidal dynamics and wave-driven longshore drift, with some of the finer-grained sediment actually being

transported over large distances (e.g., southward on the North Sea coast, including to sediment sinks offshore from the Netherlands and in the German Bight).

#### 3.18.1.1.3 Coastal flooding

Flooding affects coastal species and habitats through frequency of saline inundation. This inundation may be temporary as a consequence of episodic extreme high-water levels (e.g., from a storm surge event) or permanent (e.g., following a planned/unplanned breach of natural or man-made seaward protection). If the coastal hinterland is low-lying then potentially large-scale effects may occur during extreme events (e.g., East Anglia). Such severe flood events typically occur in combination with erosion when a protective feature is removed or damaged (e.g., as a barrier breach or changes in estuary morphology). Vulnerable habitats include coastal grazing marsh which are dominantly terrestrial/freshwater features and coastal lagoons, both of which support a large proportion of overwintering and migrating birds in key locations.

In the intertidal zone, inundation influences vegetation composition for saltmarsh communities and if the habitat is not able to migrate inland due to sea level rise, most commonly due to coastal defences, then the inundation frequency may cause a transition to mud flat and the distinctive vegetation is lost. In a healthy condition, saltmarsh is a resilient habitat and can survive extreme water levels, protecting inland locations from flooding. Simulation studies have shown that storm surge effects on saltmarsh elevation incur only minor elevational changes (Spencer *et al.*, 2015).

#### 3.18.1.1.4 Species and Habitats

It has not been possible to complement the risk data for designated areas cited above with an updated analysis of priority habitat lost or degraded by coastal erosion or flooding, representing an important evidence gap. We therefore assume the summary findings reported in CCRA2 regarding current habitat loss remain valid. Current trends have been summarised by the Office for National Statistics (2016) based upon the previous JNCC data interpreted by the time-series analysis of Beaumont *et al.* (2010, 2014; Table 3.55). The total extent of the intertidal zone in the UK has therefore decreased due to erosion from sea-level rise and coastal squeeze from hard built structures preventing natural roll back but no overall updated assessment of changes in the intertidal zone has been completed. In 2016, CCRA2 identified ca. 1200 ha of internationally protected intertidal habitat and a further 500 ha of coastal freshwater habitat that will be lost due to coastal squeeze over the next 10 years. The implications for protected species will obviously depend on the type and location of habitat affected.

Condition monitoring of coastal habitat areas also continues to show that much of it is in an unfavourable condition. In addition to protected area monitoring, saltmarsh habitat condition is now being included in Water Framework Directive (WFD) assessment of 'good ecological status'. In England, of the 40 WFD coastal/transitional water bodies assessed in 2016, 1 was of poor status, 24 were in moderate status and 15 were in good status; reduction in habitat extent and over-domination of the existing saltmarsh by one sub-habitat zone (as a consequence of coastal squeeze eroding the lower marsh) being the main issues for not meeting good status. In Wales, using the same criteria, 3 water bodies had moderate status, 7 had good status, and 3 had high status. In

Scotland and Northern Ireland, saltmarsh WFD status has not been completed yet, however in Scotland previous SNH surveys of sites >3 ha (dating to 2010-2012) showed that 67% of all sites and 69% of SSSI sites failed their condition assessment (Haynes, 2016).

**Table 3.55** Current trends in coastal habitat\* loss (ha/yr) (extrapolated from Beaumont *et al.* 2010, 2014)

	Saltmarsh	Sand dunes	Shingle	Machair
England	75.54	21.42	4.02	-
Northern Ireland	0.56	2.5	-	-
Scotland	13.5	72.86	-	23.64
Wales	15.64	9.72	-	-

\*2010 UK habitat areas (ha): saltmarsh 46631; sand dunes 70853; shingle 5852; machair 19698

Coastal habitats are dynamic features. If the ecosystem has retained the natural interaction between biotic and abiotic components, changing patterns of flooding and erosion may therefore be accommodated within a normal sequence of coastal habitat evolution, although obviously there are also limits to this natural resilience (as discussed below).

A further consideration for coastal habitats and species is the additional influence of direct climate effects, notably temperature and precipitation changes. Warm-favouring species of rocky intertidal habitats have continued to expand their range, either north along the west coast, or east along the south coast; examples include the topshell *Phorcus lineatus*, limpet *Patella depressa*, and barnacle *Chthamalus stellatus* (Burden *et al.*, 2020). Regarding precipitation changes, previous evidence reported in CCRA2 identified that dune slacks in England may be drying out due to changes in hydrological conditions. This has been linked with a reported 30% reduction in dune-slack extent in the largest protected sites between 1990 and 2012, and the remaining dune slacks show shifts from wetter to drier plant communities; however, further survey is now required to reconfirm these findings, especially in the context of recent increased frequency of wetter summers in many locations. An increase in intense rainfall events may also have negative impacts on seabirds that nest in burrows due to flooding of these sites, as occasionally occurs at present.

As with terrestrial habitats (Risk N1), some coastal habitats have considerable natural inertia meaning that, in the absence of disturbance, existing vegetation (notably dominant species) can have a strong intrinsic resistance to displacement. For example, a resurvey of dune vegetation from 89 sites in Scotland based upon a ca.34-year time lag found very limited establishment of new species from more southerly locations as may have been expected with climate warming (Pakeman *et al.*, 2015). In addition to natural resistance to change, this may be attributed to limits on dispersal to geographically isolated sites, or to management interventions that favour current species, or potentially to other climate-related factors that may predominate over temperature influence.



Regular species monitoring data is strongest for birds. Breeding seabird status has not achieved 'Good Environmental Status' (GES) as defined by the UK Marine Strategy (Defra, 2019c). Surveys have indicated over a third of UK seabird species showed declines of 20% or more in breeding abundance since the 1990s, with the decline apparently increasing in the last decade (Defra, 2020b; Mitchell *et al.*, 2020). The UK breeding seabird index (based upon the populations of 13 species) in 2018 was 28% lower than at its starting date in 1986, and only slightly above its lowest level ever recorded (-29% in 2013) (Defra, 2020b). This indicator has shown a sustained decline since the mid-2000s but in the shorter term, 5 of the index species have increased strongly (+30-40%) between 2012 and 2017 (razorbill, Arctic tern, common tern, great black-backed gull and great cormorant). The UK seabird index and its overall trends continues to exhibit a different pattern to the England index which is at least partially related to different species compositions. Some species breed only in Scotland whereas others are more widespread but with the bulk of their populations in the northern UK, meaning data is insufficient for an England-only trend. Interactions between seabirds and the wider marine environment, including the indirect effects of changes in prey availability (notably declines in sandeels) are discussed in Risk N14.

In summary, different species have varying climate sensitivities, both direct and indirect, and this also varies with location which also implicates the interaction of climate with other varying stresses (e.g., fishing pressures; pollution). Shorter-term climate variability and extreme weather events have a clear direct influence such as through severe wreck losses for some species (e.g., puffin), or from flooded burrows (Moffat *et al.*, 2020). However, scientific consensus also suggests an important indirect link to climate change through the availability of food, notably small fish such as sandeels (Howells *et al.*, 2017, 2018; Wanless *et al.*, 2018; Mitchell *et al.*, 2020). This is supported by evidence that surface feeders seem more affected than those feeding in deeper water and that there are distinctive spatial variations for some species declines (e.g., kittiwakes), which have been attributed to varying temperature impacts on sandeels and their copepod prey (Carroll *et al.*, 2017). These shifts in both predators and prey may also be contributing to a 'trophic mismatch' whereby seabirds have not kept pace with a temperature-related transition to an earlier annual sequence of sandeel life cycle events, notably in the North Sea (Defra, 2019c; Mitchell *et al.*, 2020).

The general distribution for coastal winter waterbirds shows ongoing north-easterly shifts. Waders show a positive correlation between winter temperature and abundance, and this is assumed to be due to increased food availability and reduced energy demands in warmer conditions (Pearce-Higgins and Green, 2014). Warmer winters are also associated with advanced timing for spring departure from coastal overwintering habitats to breeding grounds. Nevertheless, populations patterns are also complex, with evidence also suggesting that some waders are declining in numbers, and that this may be related to warmer, drier summers in their breeding grounds or disturbance from agricultural land-use changes (e.g., drainage of wetland habitats) (Pearce-Higgins *et al.*, 2017).

### 3.18.1.2 Future risk (N17)

#### 3.18.1.2.1 Sea-level rise and other Climate-related factors

Sea-level rise is the key determinant of changing risk magnitude in the future. When evaluating evidence for CCRA3 compared to CCRA2, it is therefore especially noteworthy that the median and upper range for UK sea-level rise projections have now been revised upwards in UKCP18 (see Chapter 1: Slingo, 2021) as further supported by recent sensitivity analysis based upon extrapolation of observed changes relative to the degree of radiative forcing and global warming (Grinsted and Hesselbjerg, 2021). This implies an increased future risk from coastal flooding and erosion hazards.

Changes in wave and tide regime remain rather uncertain but a precautionary risk management approach would recognise the potential for these regimes to also be further modified by climate change. As discussed in Chapter 1 (Slingo, 2021), some future projections for North Atlantic storms over the 21st century show an overall reduced frequency, and some indicate a poleward shift in winter storm tracks. Chapter 1 (Slingo, 2021) also highlights new climate model evidence suggesting increased winter cyclonic activity for the UK. Similar uncertainty pertains for the wave regime, especially as this is strongly influenced by frequency of large-scale atmospheric circulation patterns that are challenging to accurately simulate in climate models. Recent projections suggest a reduction in mean wave height, but an increase in the most severe wave heights, notably to the SW of the UK (e.g., Aarnes *et al.*, 2017). Analysis using an ensemble of wave models with the RCP4.5 and RCP8.5 scenarios projects the most extreme waves (100-year significant wave height) to increase by up to 5% in the SW and NW of the UK with but could decrease elsewhere (Meucci *et al.*, 2020). The current position is therefore that we cannot exclude an increase in wave-driven erosion as a plausible scenario in vulnerable locations, including inter-related effects on flooding, as notably evidenced by impacts during the recent winter of 2013/14.

Changes in local and regional tidal dynamics are known to have occurred in the past due to non-astronomical factors, such as changes in 3D coastal morphology and interaction with river flows, and therefore may be anticipated to occur in future, but the complex interactions with global sea-level rise and local meteorological factors (e.g., radiational forcing of water) make future projections rather difficult (Haigh *et al.*, 2019). Furthermore, indirect effects of climate change, such as through modified river discharges and morphological changes from managed realignment, may also be expected to have an influence. In addition, and more predictably, astronomical factors are known to influence decadal variations in local water levels, notably the amplification of the 18.6-year lunar cycle in estuaries (Wang and Townend, 2012), which will also therefore have an influence on extreme water levels, and associated flood and erosion risk, in future.

Many estuaries are important foci for nature conservation interests; however, estuaries are complex features and their response will also depend on any changes in fluvial inputs, together with surface water runoff and groundwater, in addition to the marine influence (Robins *et al.*, 2015). In general, the interaction of estuaries with the open coast will depend on the tidal asymmetry of the inlet: when the inlet is ebb-dominant (flood-dominant), sea-level rise may cause an export (import) of sediment, that acts to counter (accentuate) retreat of the adjacent coast. Larger estuaries may be especially susceptible to erosion due to the increased tidal prism, although estuary widening can partly mitigate adverse effects if an expanded intertidal area is available to provide sediment for

adaptation; by contrast, a slightly reduced tidal amplification may be expected in small estuaries (Leuven *et al.*, 2019).

Risks from both erosion and flooding will also be greater for locations that are more exposed or have intrinsic susceptibility to extreme storms. As discussed in CCRA2, more episodes of extreme storminess such as occurred during winter 2013/14 would have major implications for coastal erosion, as these stormy periods incur an extended recovery time which may potentially become greater than the interval between major storm episodes, and hence recovery does not occur. For example, a study of erosion rates at two vulnerable cliffs in Cornwall during winter 2013–2014 recorded erosion rates 3-5 times larger than the long-term average since 1948 (Earlie *et al.*, 2018).

#### 3.18.1.2.2 Coastal Erosion and Accretion

The expectation for the rate and extent of coastal erosion in the UK, based on our existing knowledge of the underlying processes, is that both will further increase. This increase is a consequence of both further relative sea-level rise and the legacy of past management decisions including from reduced nearshore sediment supply that would otherwise be available to buffer sea-level rise and facilitate habitat resilience. As a result, it is highly likely many areas of presently stable or accreting coasts will enter an erosional phase, whilst erosion rates will increase on existing eroding coastlines (Masselink *et al.*, 2020). For those areas of the coast that are protected by hard defences, the position of the coastline will become increasingly divergent from a natural dynamic equilibrium transition that would occur without defences. Our assessment of the implications of this divergence for a specific area of coastline are that removal of coastal protection would be very likely to be followed by accelerated erosion as the coastal processes adjust towards some form of equilibrium; this has been evidenced by high erosion rates following removal of defences at locations such as Happisburgh (Norfolk) (average annual erosion rates increased by 7 to 17 times: Walkden *et al.*, 2016). Alternatively, that location becomes increasingly dependent on man-made coastal protection for risk management but with consequent implications for adjacent sections of coast (e.g., through disruption to longshore sediment transport).

Indicative projections of coastal erosion extending to 2050 and 2100 have been derived based upon extrapolation of current rates for England and Scotland, providing general inferences of areas at risk, although currently no further information is available to update CCRA2 based upon implications for priority habitats. Hence, in England analysis for the NCERM (Rogers *et al.*, 2008) of the area of SSSI 'at risk' from erosion has produced for 2050 a central estimate (50% likelihood) of 1600 ha and an upper estimate (5% likelihood) of 2000 ha. Comparative reference values for 2100 were 2800 ha (central estimate; or 3100 ha including complex cliffs) and 3500 ha (upper estimate; or 4400 ha including complex cliffs). These projections are indicative of expected changes in risk but do not yet incorporate a recognition that SSSI status is often related to the dynamic evolution of a habitat or underlying landform, rather than being a static feature, and erosion of sediment from one location may actively support habitat development at another.

In Scotland, the Dynamic Coast project has not yet projected future coastal erosion risk due to changing climate drivers, but implications have been derived by assuming a continuation of the same recent historic rates since the 1970s (Fitton *et al.*, 2016; Hansom *et al.*, 2017). This would imply that by 2050, ca. 350 ha of the SEPA indicative coastal floodplain (i.e., the notional area of risk

exposure for a 1-in-200-year flood event) would be affected. Within this zone it can be assumed that low-lying coastal dunes, machair and salt marshes, together with associated terrestrial or freshwater habitats, would be mostly at higher risk, especially if erosion extends above the MHWS level as occurs during severe storm events. In addition to erosion, the coincidence of erosion with flood risk would be likely to induce a further change in flood frequency and extent of inundation, although at some sites, localised accretion may provide some protection. In terms of designated protected areas, these forward projections indicate that 88 ha of NNR, 223 ha of SAC, 266 ha of SPA, and 360 ha of SSSI would be notionally at risk of expected erosion, depending on the rationale for designation (in some cases erosion may have beneficial outcomes, or be consistent with dynamic geomorphic evolution of habitats balancing erosion and accretion; also noting that some locations have multiple designations). These estimates are indicative, and likely to be further refined based on use of future climate change scenarios and analysis that accounts for the 3D geomorphology of dynamic coastal habitats rather than just the assumed changes in MHWS based on a simple planform assessment. More detailed site assessments are also likely to refine these estimates, as erosion (and potentially accretion) at each site involves the interaction of natural processes with the additional effects of changing sea levels, in addition to other possible factors (e.g., tidal dynamics, wave regime), and human interventions on the coastal zone.

#### 3.18.1.2.3 Coastal Flooding

Indicative assessments of the risk of coastal flooding for designated nature conservation sites have been provided by the recent CCC Floods Study (Sayers et al., 2020; Table 3.56), based upon central estimates for the scenarios of 2°C and 4°C global warming in 2100 as related to sea level rise (wave and tidal regime and coastal/fluvial tidal flooding combinations were assumed to remain as at present). These also show a significantly increased flood risk for the future, except for Scotland, and especially for England. However, some caution is required in interpretation as the methodology was not designed to account for the dynamics of the natural environment and again, as above, the actual implications will depend on the rationale for site designation (some species and habitats being more vulnerable to saltwater flooding than others).

**Table 3.56.** Increase in designated areas at significant risk of coastal flooding (frequency of 1 in 75 year or greater) for England, Scotland, Wales, and Northern Ireland, for the 2050s and 2080s on pathways to 2°C and 4°C global warming by 2100 with low population, from Sayers *et al.* (2020). NB. Risk is assessed to areas to landward of coastal defences but does not include changes in inundation frequency and associated risk for habitats on seaward side.

ENGLAND						
Assets at significant risk	Baseline (Ha)	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C	
Most Important habitats exposed to frequent flooding	48,434	57%	64%	65%	69%	
Ramsar area in probability bands - Significant	18,649	49%	55%	56%	58%	
SAC area in probability bands - Significant	11,647	68%	76%	79%	85%	
SPA area in probability bands - Significant	18,139	59%	65%	66%	69%	
NORTHERN IRELAND						
Assets at significant risk	Baseline (Ha)	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C	
Most important habitats exposed to frequent flooding	1078	18%	33%	38%	55%	
Ramsar area in probability bands - Significant	234	24%	44%	51%	74%	
SAC area in probability bands - Significant	224	0%	0%	0%	1%	
SPA area in probability bands - Significant	621	22%	40%	47%	68%	
SCOTLAND						
Assets at significant risk	Baseline (Ha)	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C	
Most important habitats exposed to frequent flooding	69,784	2%	3%	4%	5%	
Ramsar area in probability bands - Significant	21,784	2%	4%	4%	6%	
SAC area in probability bands - Significant	20,338	2%	3%	4%	5%	
SPA area in probability bands - Significant	27,663	2%	3%	4%	5%	
WALES						
Assets at significant risk	Baseline (Ha)	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C	
Most important habitats exposed to frequent flooding	40,006	23%	28%	28%	32%	
Ramsar area in probability bands - Significant	8,361	33%	39%	40%	45%	
SAC area in probability bands - Significant	21,501	22%	26%	26%	28%	
SPA area in probability bands - Significant	10,144	18%	23%	23%	27%	

#### 3.18.1.2.4 Species and Habitats

In response to ongoing sea-level rise, the natural response of coastal habitats and landforms would be to roll-over and migrate landwards, where topography allows this (i.e., without steeply-rising ground to impede this), meaning that habitats associated with barrier coastlines and estuaries would be maintained in their relative shoreline position. However, this geomorphic evolution will be strongly influenced by other local factors including both concurrent climate-driven processes (waves, tides) and past/present coastal management. Longshore factors will also continue to be a key influence, especially as they are a dominant control on many areas of the UK coastline, hence erosion and accretion will likely occur at different rates and locations alongshore in addition to shoreward profiles, especially where hard defences interrupt the natural response in either direction.

Existing trends for loss of intertidal area are therefore expected to continue, dependent on sea level rise scenario and any change in management regime, and potentially any additional effects from wave and tidal dynamics. For saltmarshes, Horton *et al.* (2018) showed a greater than 80% probability of retreat in extent for the whole of Great Britain by 2100 under a high climate change scenario (RCP8.5) by 2100; for higher risk areas of southern and eastern England, an 80% probability of marsh retreat would occur by 2040. This can be compared with a low climate change scenario (RCP 2.6) where there is a >20% probability of an expansion or of relatively stable outcomes for saltmarsh over the next 200 years for Scotland and NW England but for which there still remains a >80% probability of marsh retreat beyond 2100 for southern and eastern England.

A key influence on the future resilience of habitats will be sediment supply, notably for saltmarsh and mudflat, dune systems, and shingle features, together with the role of other climate variables. With increased sediment supply, future projections for the loss of intertidal area referred to above, may be too pessimistic as active saltmarsh habitats can accrete sediment in-situ, even potentially for considerably higher rates of sea-level rise than at present (Ladd *et al.*, 2019). However, for many areas of the UK coastline, the existence of coastal defences means that intertidal zones are usually in a state of sediment depletion, which imposes constraints on their natural adaptability even with present rates of sea-level rise. Habitat composition is also likely to change: for example, warmer temperatures could favour the existing invasive *Spartina anglica*, causing it to replace native cordgrass, and potentially reducing soil stability which then further increases erosion risk (Ford *et al.*, 2016).

For England, the NCERM (Rogers *et al.*, 2008) has estimated that in the near-term (mid-2020s), some 500 ha of freshwater habitat in the coastal zone will be lost due to coastal squeeze. It has also been estimated that an average of around 4-6% priority freshwater habitats in the coastal floodplain could be lost per year due to saltwater inundation, most of this being in designated areas. However, this assessment does not include episodic inundation caused by extreme storm surges. Some vulnerable habitats such as freshwater grazing marsh are very likely to become at greater risk from increased frequency of coastal flooding either due to overtopping of natural or artificial seaward defences, or due to a major breach of these defences during an extreme event. Whilst this may eventually facilitate a transition to new intertidal habitat (saltmarsh or mudflat), loss of the freshwater grazing marsh may be significant for species that depend on it (e.g., waterbirds, invertebrates, and some

plants), and even if new grazing marsh is created elsewhere there is no guarantee that these species will be able to colonise it (e.g., due to different habitat conditions or constraints on species dispersion).

In addition to constraints related to sediment supply, shingle has rapid drainage and therefore an increased frequency of extended dry periods would be likely to modify vegetation and soil structure through changes to groundwater levels, also increasing vulnerability to further disturbance because recolonization rates are therefore likely to be slower. In some locations, increased disturbance and warmer temperatures may favour invasive species (e.g., Hottentot fig *Carpobrotus edulis*, which is frost-sensitive but already extensive in southern England and has also spread to Wales, Northern Ireland and even recorded by the Biological Records Centre at locations in western and northern Scotland: Burden *et al.*, 2020).

Sea-level rise will also have an important influence on low-lying coasts by modifying groundwater levels and potentially the frequency and extent of waterlogging for some priority habitats. Changing groundwater levels will modify open-water areas, which are important for wintering birds, and may cause substantive losses to ephemeral areas such as dune slacks that are important habitats for rare taxa, such as some amphibians (Rhymes *et al.*, 2016). Similarly, for machair habitats, future biodiversity will strongly depend on water management and continued effective drainage of excess precipitation (much of the machair is artificially drained) and prevention of marine incursion through breaching of dune systems or wave overtopping, of which the risks will especially increase due to ongoing sea level rise (Angus, 2018; Angus and Hansom, 2021).

Based upon a continuation of current climate pressures, some seabirds may become extinct in the UK by 2100 (e.g., Leach's storm petrel; great skua; Arctic skua) whilst other species are likely to have reduced ranges (e.g., black-legged kittiwake; Arctic tern; auks) (Burden *et al.*, 2020). Modelling work based upon the indicator species used for the UK breeding seabird index (see 'Current risk' above) has inferred that even the index species currently showing increased populations (excepting common tern) are at significant risk of future declines due to climate change effects (Davies *et al.*, 2020).

Six of the priority non-breeding UK waterbird species, have been identified as at high risk of UK range loss, with arctic-subarctic breeding species especially vulnerable to major changes in their breeding grounds; a further 14 species have been identified at moderate risk, whilst 20 species are projected to benefit through range expansion (Mendez *et al.*, 2018). These risks and opportunities may be expected to lead to considerable species turnover at individual protected areas: the same study found only 10 of 57 SPAs were projected to lose all qualifying species by 2050, and 11 SPAs by 2080. Projected increases in abundance could result in six to seven new designated sites supporting internationally important numbers, although this will require continued availability of intertidal and coastal grazing marsh habitats despite sea level rise. As noted above, there are important uncertainties in the projected future responses of both estuaries and the intertidal zone, due to the interaction of multiple morphodynamic and hydrodynamic factors with sea-level rise. These could have additional implications for species such as waterbirds that rely on both the extent and quality of habitat for food and shelter. As discussed in section 3.18.2, a key risk management issue for

adaptation will be whether habitat loss due to sea-level rise is compensated by habitat creation shorewards, either naturally or through additional managed interventions.

#### 3.18.1.3 Lock-in (N17)

The main lock-in effect is that most sections of the coast are continuing with 'hold the line' (HTL) policies, either as defined by the Shoreline Management Plan (SMP) or in practice. In the latter case, as discussed further below in terms of adaptation (section 3.18.2), the practical issues occur due to local resistance to a shift away from HTL. The end-result is to create an unsustainable long-term legacy for the coastal zone as the shoreline becomes further out of its dynamic equilibrium position as sea-level rise increases. This means that when a shift in approach is eventually made towards a more sustainable long-term policy (some SMPs indicate a shift away from HTL in a future management epoch), there can be difficulties in establishing a non-abrupt transition away from the current position, meaning that local erosion rates can increase substantially. It is our assessment that limited short-term protection from erosion and flooding risk is therefore in many locations being achieved at the expense of a notable increase in long-term risk, unless coastal protection schemes are substantially upgraded, which for many locations would be considered too costly unless to protect major settlements (Chapter 5: Kovats and Brisley, 2021) or infrastructure (Chapter 4: Jaroszweski, 2021).

It is also worth noting that a HTL policy may vary according to region and therefore current SMPs sometimes contain inconsistencies. For example, a shingle barrier may be defined as a HTL feature or to have no-active intervention. In the case of HTL, this may involve engineering intervention through re-profiling of the shingle barrier to maintain it in its current planform position, but with the risk that, by not allowing natural rollover, it is increasingly exposed to the possibility of a catastrophic breach as the lower foreshore continues to adjust to changing hydrodynamic drivers.

In consequence, areas with HTL policies will need to regularly re-evaluate their full implications in both short-term and long-term, including recognition that HTL coastal segments may affect other adjacent areas through modified sediment supply. With regard to coastal habitats, this means that in some locations there are difficult decisions to be made between the conservation of intertidal habitats through managed realignment of coastal defences or conservation of inland habitats (e.g., freshwater grazing marsh) that rely on defences to remain in situ and would otherwise require compensatory habitat elsewhere. However, compensatory habitat for displaced freshwater or terrestrial habitats may then require re-allocation of farmland or other land uses, necessitating extensive consultation and negotiation. Most notably for coastal biodiversity, realisation of opportunities requires a managed transition away from maintaining the status quo, providing accommodation space for habitat evolution. Wider benefits of coastal habitats through alleviation of flooding and erosion hazards also need to be more explicitly incorporated into management decisions.

#### 3.18.1.4 Thresholds (N17)

The rate of sea-level rise is a key threshold for the erosion rate and flood risk in combination with available sediment supply. When the rate of sea-level rise exceeds the buffering capacity of habitats



to remain in situ (which is also sustained by sediment supply) then a step change to more rapid erosion can occur. The saltmarsh analysis by Horton *et al.* (2018) cited above used Holocene sedimentary records to infer that marshes become nine times more likely to retreat than expand when relative sea-level rise rates are  $\geq 7.1$  mm/yr. Threshold effects also occur on coasts with hard defences as sea-level rise increases the hydrodynamic loading on the defences and on habitats on the seaward side, therefore increasing the detrimental effects of coastal squeeze. If the defences are removed or breached, then a rapid step change of the shoreline can also occur to a new dynamic equilibrium position, which may incur rapid habitat change or loss for areas formerly landward of defences. Threshold effects can also occur with changes in wave energy regime (wave height, direction etc.) and during extreme events with abnormal high-water levels.

#### 3.18.1.5 Cross-cutting risks and inter-dependencies (N17)

There are many cross-cutting interactions involved that together require an integrated approach to coastal management. Erosion and flooding are inter-related through coastal dynamics and isolated management responses to one type of hazard can accentuate the other elsewhere on the coast or exacerbate the risk in the longer term (Pollard *et al.*, 2019). Coastal habitats have an important hazard alleviation role that when degraded can increase negative outcomes for infrastructure (Chapter 4, Risk I3: Jaroszweski, Wood and Chapman, 2021), the built environment (Chapter 5, Risk H4: Kovats and Brisley, 2021), agricultural land (Risk N6), and associated businesses (Chapter 6, Risk B1, B2: Surminski, 2021). Coastal habitats and species also provide important cultural benefits to people including through amenity value and landscape character (Risk N18) whilst also providing inshore fisheries and carbon storage/sequestration benefits (Risk N5). Furthermore, it is important to recognise that coastal habitats also contain many cultural and historic assets (e.g., related to maritime activity and coastal defence) and decisions on future management options also need to take account of these (see Chapter 5: Kovats and Brisley, 2021). For example, on the Welsh coastline over 100,000 historic assets of all periods and types have been identified, and Cadw have identified 16% of these to be at risk from sea level rise. In many instances, coastal cultural heritage cannot be moved and if physical loss is inevitable there is a need for that heritage to be continued through other forms (e.g., full documentation, or the use of narrative storytelling to capture the cultural and landscape/seascape context). In a dynamic coastal setting, challenges in integrating policies for conservation of both the natural environment and cultural heritage therefore need to be better recognised and addressed more strategically in coastal planning. There is also increased interest in using enhanced public engagement and citizen science in understanding the linkages between coastal heritage and natural processes in the context of climate change (e.g., Scotland's Coastal Heritage at Risk Project: Dawson *et al.*, 2020).

A further complicating factor in some locations is the interaction with invasive species that can modify the natural succession of coastal ecosystems. A prominent example is the presence of the invasive hybrid cord grass *Spartina anglica*, notably in southern England (Biological Records Centre, 2021). This can increase local sedimentation rates and colonisation of mudflats to saltmarsh, whilst also negatively impacting pioneer communities of saltmarsh, especially on *Salicornia* communities. However, the long-term outcome of these interactions in a changing climate remain uncertain.

Finally, specifically in relation to coastal ecosystem services, there are likely to be important implications for management of this risk in relation to societal inequalities (see 'section 3.18.1.7 below), notably for vulnerable coastal communities that are either directly or indirectly reliant on the continued availability of natural alleviation of coastal hazards (see Chapter 5: Kovats and Brisley, 2021).

#### 3.18.1.6 Implications of Net Zero (N17)

There are potential implications through increased development of coastal renewable energy sources, which may have both positive and negative impacts on coastal habitats and species. Also, coastal habitats (notably saltmarsh) can be important carbon sinks: for further discussion of the important opportunities for 'Blue Carbon' through habitat creation/restoration, as would occur with a larger-scale shift towards managed coastal realignment, see Risk N5 (section 3.7). Coastal habitats are at present not included in the UK GHG emissions inventory, ostensibly due to the large uncertainties involved with regard to emissions and sequestration values, but this should not be a significant barrier for a Tier 1 type assessment (including sensitivity testing of different emission factors), especially by comparison with the similar uncertainties in the LULUCF sector (as reported elsewhere in this document, including for peatlands which are now planned to be included). The key issue here is the significant contribution that coastal habitats could make to reducing atmospheric GHG concentrations, rather than assumed impediments in accounting procedures.

#### 3.18.1.7 Inequalities (N17)

Implications for loss of ecosystem services, notably if continued habitat loss results in increased risk from coastal flooding and erosion, are also likely to have implications for vulnerable communities in affected areas (see Chapter 5: Kovats and Brisley, 2021) that currently benefit from natural coastal protection (e.g., sand dunes, shingle bars, intertidal zone). This could therefore exacerbate social inequalities, as for example in locations where SMPs and government cost-benefit calculations imply no further intervention will occur and structural defences removed or allowed to degrade, and therefore it can be identified that there is an assumed dependence on natural coastal protection.

#### 3.18.1.8 Magnitude scores (N17)

Magnitude categories in Table 3.57 are based on expert judgement and assessed in terms of existing or expected impacts on biodiversity (including viable metapopulation sizes), ecosystem functioning, and ecosystem services (excepting carbon storage – Risk N5). This approach is also followed because indicators based upon species numbers or habitat area are only crudely indicative of systemic risks. Risk magnitude is assessed as increasing from medium at present to high in the future (all climate projections) due to the strong relationship with sea-level rise and other climate factors and the current constraints on natural adaptive capacity. Confidence in this assessment is medium for the present but reduces to low-medium in future (only low confidence for Northern Ireland for both present and future). This is because evidence for changes in priority species and habitats is limited (more detailed evidence is often available only for certain locations), and although there is good general information on the present-day extent of coastal impacts, the combination of multiple factors in future (including socioeconomic factors) means the full risk magnitude is difficult to project forwards.

**Table 3.57** Magnitude score for risks and opportunities to coastal species and habitats due to coastal flooding, erosion, and climate factors

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium (Medium confidence)	High (low-medium confidence)	High (low-medium confidence)	High (low-medium confidence)	High (low-medium confidence)
<b>Northern Ireland</b>	Medium (Low confidence)	High (low confidence)	High (low confidence)	High (Low confidence)	High (Low confidence)
<b>Scotland</b>	Medium (Medium confidence)	High (low-medium confidence)	High (low-medium confidence)	High (low-medium confidence)	High (low-medium confidence)
<b>Wales</b>	Medium (Medium confidence)	High (low-medium confidence)	High (low-medium confidence)	High (low-medium confidence)	High (low-medium confidence)

### 3.18.2 Extent to which the current adaptation will manage the risk (N17)

#### 3.18.2.1 Effects of current adaptation policy and commitments on current and future risks (N17)

##### 3.18.2.1.1 Flood and coastal erosion risk management policies

##### 3.18.2.1.1.1 UK-wide responsibilities and strategies

Across the UK, responsibilities for flood and erosion risk management are varied and operate at multiple scales (see below). This has increased relevance in terms of both the delivery of strategic responses to climate change and the role of the natural environment in those strategic responses through: (i) protection for priority species and habitats; (ii) protection for designated nature conservation areas; (iii) multiple societal benefits provided by coastal ecosystems and their interaction with people, settlements, infrastructure, and businesses.

Across all the UK, under the implementation of the Floods Directive (UK Flood Risk Regulations (2009) and devolved equivalents), Flood Risk Management Plans (FRMPs) and Flood Risk

Management Strategies (developed to co-ordinate local plans in Scotland) have been produced for coastal districts.

In each case, national strategic guidance for coastal management aims to ensure decisions are sustainable. The key implementation mechanism at local and regional level is usually through Shoreline Management Plans (SMPs), which are based on natural boundaries (littoral sediment cells) rather than administrative units. All of England and Wales is covered by SMPs, but only part of Scotland (ca.8% of the coastline), and none of Northern Ireland has an SMP or equivalent plan. Where an SMP is available, it is intended that it contributes to an area's overall flood risk management plan including to provide a joined-up approach across risk management authorities. By identifying recommendations required to achieve a sustainable coast, SMPs also have a key role in conserving habitats and species.

#### 3.18.2.1.1.2 Shoreline Management Plans (SMPs)

The SMP process in combination with active coastal partnerships has been shown to facilitate a constructive pathway towards sustainable and integrated coastal zone management (e.g., Ballinger *et al.*, 2020), although the quality of plans is variable, with not all following and implementing the holistic long-term vision established by the earliest plans in the current implementation cycle (2<sup>nd</sup> generation in England and Wales). SMPs define coastal management decisions in the short-term (0–20 years), medium-term (20–50 years) and long-term (50–100 years) although these epochs are defined for England and Wales based on the start of the current (i.e., second-round) implementation cycle (2009–11), rather than being incrementally updated; therefore, the current short-term epoch will in end in a few years. SMPs remain advisory rather than statutory instruments, which can mean that in practice the recommendations are not necessarily funded or implemented. Currently, in England and Wales a SMP Refresh is underway to incorporate new legislation, knowledge and information into existing plans, including climate change projections, and to provide supplementary guidance for helping to manage the implementation of SMP policies, including a consistent template for SMP action plans (further details on SMPs are provided in Chapter 5: Kovats and Brisley, 2021). This SMP Refresh is therefore anticipated to initiate a new planned implementation cycle, although details of how this will actually change plan outcomes (including for both climate change responses and protecting habitats and species) is yet to become available or independently assessed. Therefore, at present, we do not have independent evidence on how the SMP Refresh will change existing SMP plans or their implementation in practice.

A major challenge for adaptation is that plans, as outlined by SMPs based upon analysis of local evidence, are not being fully delivered (House of Commons, Environment, Food and Rural Affairs Committee, 2019). Analysis by the CCC (2018a) for England has indicated that 111 km of coastline had been realigned by 2016, but that the average realignment rate of 6 km/yr for 2000–2016 falls well short of aspirations in SMPs to realign 550 km by 2030 (ca. 30 km/yr). Similarly, habitat creation schemes were found to total 2220 ha by 2016 (a rate of 130 ha/yr) which also falls short of ambitions in the SMPs to create 7500 ha by 2030 (ca. 400 ha/yr). Equivalent analysis for Wales, Scotland or Northern Ireland is not available. Further discussion of progress regarding current habitat compensation programmes is provided below.

In some locations there is a notable mismatch between local plans in coastal areas and the relevant SMP for that area. CCC (2018a) analysis found that up to one third of coastal local plans in England show no evidence of using the SMPs as their required evidence base; for the rest of the UK no equivalent review has taken place therefore the position there remains unclear. It has also been noted that the requirement for the SMPs to underpin coastal development strategies in England has been removed from the 2018 revision of the National Planning Policy Framework (NPPF) and instead moved into the Planning Practice Guidance (PPG), which may be considered to give it lesser importance, although PPG can have utility as a working policy document to include best practice. Furthermore, the CCC (2018a) also found that local plans in England only extended to 2036 at best, therefore not encompassing the full long-term recommendations of SMPs. The NPPF (England) identifies that areas "likely to be affected by physical change to the coast" should be demarcated as Coastal Change Management Areas (CCMAs) and the local planning authority should then ensure that "inappropriate development" is avoided. Physical change in this context refers to coastal erosion rather than flooding. However, in practice CCMAs are not defined for areas where a HTL policy is in place, despite the likelihood that this policy may be (or become) unsustainable due to climate change. Hence, this mechanism to assess and discourage inappropriate development is not fully activated, and problems from policy lock-in may therefore be perpetuated.

Discrete coastal segments are distinguished within SMPs as local management units. However, the basis for these has been criticised for being defined primarily based upon the hazards currently experienced, or the urban or rural characteristics of the hinterland, neglecting other considerations that are important for risk assessment including broader social, economic and environmental vulnerability contexts, or the compound nature of the hazard in many locations (Townend et al, 2021).

A further challenge for SMPs, and coastal zone management in general, is addressing more recent projections for high rates and magnitudes of sea-level rise (Chapter 1: Slingo, 2021). Implementation of current plans is usually based upon a single future projection that has been carried forward from past assessments and also contain notable inconsistencies. Analysis in England and Wales has shown that the different planning processes and timetables involved for SMPs and CFMPs (Catchment Flood Management Plans, which are developed for tidal rivers) has led to inconsistencies regarding use of future sea level rise projections provided through government guidance (Kuklicke and Demeritt, 2016).

A more robust approach to adaptation planning would include a range of range of future projections, including the possibility of significantly higher upper-end estimates (>10 mm/yr) that may make some current preferred policies for specific sections of coast unviable with regard to the stated outcomes. As noted in the CCRA2 Evidence Report, a notable exception here is the Thames Estuary 2100 project in which multiple adaptation pathways were scoped consistent with a range of sea-level rise projections, but since CCRA2 this exemplar has not been followed up through a wider range of similar example plans for the UK coastline to our knowledge.

Current policy developments for each nation can be summarised as follows:

### 3.18.2.1.1.3 England

Defra has overall national responsibility for policy on flood and coastal erosion risk management in England, with the Environment Agency having a strategic overview to ensure that decisions by local authorities and others on the coast are made in a joined-up manner, whilst also being the lead organisation for main rivers and tidal flooding. Erosion management is the responsibility of coastal local authorities. The Environment Agency works together with Coastal Protection authorities to develop Shoreline Management Plans which aim to identify the most sustainable approach to managing coastal flood and coastal erosion risks.

The Government has now proceeded to develop a new policy framework and strategy for the coming decades, the objectives for which have been set out in the new flood and coastal erosion risk management policy statement and associated National Flood and Coastal Erosion Management Strategy (EA, 2020; HM Government, 2020). The Strategy and Statement recognise the key role of natural processes in risk reduction for people and places, together with the need to develop more flexible approaches (adaptation pathways) to correct current problems with lock-in (as discussed above in 3.18.1.3, past decisions to defend a section of coast have continued to have a strong influence on current decisions, despite increased recognition that climate change is modifying coastal processes). The Strategy and Policy Statement include a commitment to 'double the number of government-funded projects which include nature-based solutions to reduce flood and coastal erosion risk' although as yet no further information on these projects (e.g., scale; coastal locations etc.) is available. Funding (£150 million across 25 local areas) will target projects that demonstrate how practical innovative actions can work to improve resilience to flooding and coastal erosion. It is proposed that the FCERM strategy will provide annual progress reporting on a series of measures consistent with the Floods & Water Management Act. In addition, it is expected that changes to the formula for allocating funding for flood and coastal defence schemes across England will result in increased payments for flood schemes which also create a range of environmental benefits.

It is also intended that there will be a review of the effectiveness of existing planning policy on Coastal Management Areas and the current mechanisms and legal powers Coastal Protection Authorities can use to manage the coast. National policy for Shoreline Management Plans will also be reviewed to ensure local plans are transparent, continuously review outcomes and enable local authorities to make robust decisions for their areas.

The dominant SMP policy at present is Hold the Line (HTL: covering 52% of the coast) with a much smaller proportion defined for Managed Realignment (MR: 10%), and the remainder being No Active Intervention (NAI: 38%). For future epochs, the overall balance changes, although not greatly, both for 2025-2055 (HTL: 46%, MR:16%, NAI: 38%) and 2055-2105 (HTL: 46%, MR:15%, NAI: 39%). This also disguises considerable regional variation (e.g., much of south-west England is designated as NAI, whereas much of south-east or east England remains HTL). However, as noted above, a SMP Refresh process is now underway to reappraise plans in the light of new evidence and policy objectives, with strategic oversight by the Environment Agency and updated guidance to supplement the previous guidance published in 2006. It is also intended that SMPs become more like 'living documents' that are regularly reviewed and updated than they have been in the past, including with the 5-year cycle for Local Plans. As part of this process, research to better understand and contextualise historic

coastal change is currently underway, including issues associated with 'coastal squeeze' (see 3.18.2.1.2 below).

#### 3.18.2.1.1.4 Northern Ireland

In Northern Ireland, the Rivers Agency operates as a strategic agency of the Department for Infrastructure to address flooding issues. There is no legislation in place to specifically address coastal erosion or assign responsibilities (hence there is no department with lead responsibilities); instead, coastal assets are looked after by the respective government department whose responsibilities most closely coincided with the property or asset at risk from erosion (the 'Bateman formula': 1967). This piecemeal approach has tended to act against a strategic approach to coastal erosion risk management which is exacerbated by rather limited data and knowledge on current risks (Cooper *et al.*, 2016; DAERA, 2019b). Nevertheless, the responsibility for the appropriate management of coastal changes lies principally with DAERA and DfI, with DAERA responsible for nature conservation. A recent baseline study and gap analysis of coastal erosion risk management in the country (DAERA, 2019b) also identified a lack of strategic coastal data and an ineffective current policy and monitoring framework by comparison with other countries. DfI Rivers is currently undertaking a coastal mapping update study and a high-resolution 3D coastal topographic survey (LiDAR and satellite-derived bathymetry) has recently been commissioned, which will both aim to provide an improved monitoring baseline for risk assessment. Similarly, work underway through the UK-wide Coastal Flood Boundary Conditions Update project should provide improved and up-to-date data on extreme still water sea levels for flood risk mapping. The Northern Ireland Marine Plan (2018) includes climate change, coastal processes, land/sea interactions, and cumulative impacts as core components, all of which are highly relevant to the coastal environment, but the Plan is yet to be adopted by government.

There has been no development of SMPs in Northern Ireland (or an equivalent coastal planning mechanism), although there is increasing awareness of the need to approach coastal issues more strategically and to improve data collation (Cooper *et al.*, 2016). Current efforts are therefore focussed on collating baseline data to confirm the scale of the challenge for both flooding and erosion. For example, although current data for recent decades suggests that the acceleration in the rate of relative sea-level rise has been similar (ca. 2.3mm/yr) to the rest of the UK and Ireland after local land movements have been accounted for (see Chapter 1: Slingo, 2021), the quality of data has been questioned due to discrepancies and over-reliance on the tide gauge at Belfast (Murdy *et al.*, 2015). This therefore remains a crucial issue for distinguishing shorter-term periodic variations from the long-term sea level trend, and therefore resulting implications for both current and future coastal change (Orford and Murdy, 2015).

#### 3.18.2.1.1.5 Scotland

The Scottish Government has national responsibility for policy on flood management, with SEPA as strategic flood risk management authority. For coastal protection, Scottish Government has national responsibility whilst local authorities have powers on protecting land from incursion by the sea in their respective areas, although legal responsibility remains with the landowner. Whilst SEPA are not responsible for the management of coastal erosion, consideration has been given to this in FRMS by identifying areas that are likely to be susceptible to erosion, as well as areas where erosion could exacerbate flood risk (although there is scope for further improving flooding/erosion interactions).

Scottish Planning Policy clearly states that: *"...new development requiring new defences against coastal erosion or coastal flooding will not be supported except where there is a clear justification for a departure from the general policy to avoid development in areas at risk. Where appropriate, development plans should identify areas at risk and areas where a managed realignment of the coast would be beneficial."*

The government-funded Natural Flood Risk Management Network aims to share knowledge and best practice on natural flood management. The policy framework is also supporting Dynamic Coast which has conducted a first-phase assessment of coastal erosion risk; its second phase will investigate the resilience of Scotland's natural coastal defences (for example, identifying where low dunes may breach), estimate how future climate change may exacerbate flooding and erosion, and develop risk management, adaptation and resilience plans. This will inform ongoing development of SMPs and Flood Risk Management Strategies, including further scope for nature-based solutions, of which there are presently a range of guiding examples including the recent scheme at West Sands (St. Andrews) in response to the 2010 storm surge, and the community-based investigation of such schemes on the machair coast of Uist (Angus and Hansom, 2021). Guidance has also been produced on the implications of Dynamic Coast for development planning (NatureScot, 2020). However, there remain many important evidence gaps and, although monitoring data are available for some locations, it is often rather lacking at national scale, notwithstanding the complexity of Scotland's complex mainland and island coastline. The next phase of Dynamic Coast research will therefore be strongly reliant on improved data acquisition, including to develop robust future erosion projections consistent with the full range of climate change projections for relative sea level rise and other erosion-related parameters (e.g., wave regime). In this regard, it can be noted that adaptation policy could be further enhanced by better inclusion of key indicators on coastal change, reflecting not only species and habitat change, but also progress on adaptation responses, such as through realignment schemes, as supported by improved monitoring data.

#### 3.18.2.1.1.6 Wales

In Wales, responsibilities for flood and coastal erosion risk management are strategically implemented by Natural Resources Wales (NRW). The recently published National Strategy for Flood and Coastal Erosion Risk Management (Welsh Government, 2020) provides a 10-year strategy proposing a shift towards more nature-based solutions and for coastal groups to report annual progress on their SMP action plans through the Wales Coastal Group Forum. In the National Strategy, the Welsh Government also commits to develop and communicate a coastal adaptation toolkit to facilitate engagement with communities, recognising challenges now occurring with vulnerable communities (e.g., Fairbourne: see Chapter 5: Kovats and Brisley, 2021). The integrity of protected (or nationally significant) coastal habitats in Wales is managed through the Conservation of Habitats and Species Regulations 2017. Habitat Regulation Assessments were undertaken for the 4 SMPs in Wales (although using different methodologies), which estimated the amount of compensatory habitat that will be needed to implement the various SMP policies over the 100-year period. The methodology is now being refined and made more consistent to establish an agreed target for all SMP policies in Wales, in conjunction with sediment- and erosion-tracking research through the Wales Coastal Monitoring Centre.



#### 3.18.2.1.1.7 Flood Risk Management Benefits

An indicative assessment of the benefits from a continuation of the current level of adaptation for reduced flood risk to designated nature conservation sites shows that significant gains may be achieved for England and Northern Ireland, and to a lesser extent for Wales (Table 3.58) when compared against the reference risk level presented above without further adaptation (Table 3.56). However, the current level of adaptation produces little extra risk reduction for Scotland (partly because this study assessed the reference risk level as relatively low). Specific assumptions about the definition of current adaptation are available in the Sayers *et al.* (2020) report.

**Table 3.58** Change in nature conservation assets at significant risk of coastal flooding (frequency of 1-in-75-year or greater) for the four nations assuming continuation of current adaptation (Sayers *et al.*, 2020). Note that the effectiveness of the adaptation strategies needs to be ascertained by comparing with Table 3.56.

ENGLAND					
Assets at significant risk	Baseline (Ha)	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C
Most important habitats exposed to frequent flooding	48,434	28%	36%	36%	60%
Ramsar area in probability bands - Significant	18,649	31%	39%	39%	54%
SAC area in probability bands - Significant	11,647	26%	36%	36%	74%
SPA area in probability bands - Significant	18,139	25%	32%	32%	56%
NORTHERN IRELAND					
Assets at significant risk	Baseline (Ha)	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C
Most important habitats exposed to frequent flooding	1078	33%	55%	62%	79%
Ramsar area in probability bands - Significant	234	24%	44%	51%	74%
SAC area in probability bands - Significant	224	74%	109%	114%	117%
SPA area in probability bands - Significant	621	22%	40%	47%	67%
SCOTLAND					
Assets at significant risk	Baseline (Ha)	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C
Most important habitats exposed to frequent flooding	69,784	2%	4%	4%	5%
Ramsar area in probability bands - Significant	21,784	2%	4%	4%	6%
SAC area in probability bands - Significant	20,338	2%	3%	3%	5%
SPA area in probability bands - Significant	27,663	2%	4%	4%	5%
WALES					
Assets at significant risk	Baseline (Ha)	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C
Most important habitats exposed to frequent flooding	40,006	15%	19%	19%	27%
Ramsar area in probability bands - Significant	8,361	18%	24%	24%	38%
SAC area in probability bands - Significant	21,501	13%	17%	17%	25%
SPA area in probability bands - Significant	10,144	16%	20%	20%	22%

### 3.18.2.1.2 Habitat creation schemes

#### 3.18.2.1.2.1 UK-wide

Despite existing challenges, there is an increasing amount of land assigned to managed realignment and habitat creation objectives, primarily in England. The Online Managed Realignment Guide (ABPmer, 2019) listed 51 managed realignment projects in the UK by 2019; in addition to this, 24 regulated tidal exchange projects have been completed delivering a further 300 ha of coastal habitat, as well as 18 restoration projects involving sediment recharge from ports and harbours. Many of these are small-scale initiatives, but size has been increasing during recent years. Most of the habitat created has been saltmarsh and mudflat in the intertidal zone. For saltmarsh, a total area of 2647 ha has been created from 1991 to 2017 (ABPmer, 2019). The remainder of new habitat consists largely of saline lagoons and transitional grasslands and associated terrestrial habitats. Habitat compensation programmes aim to create new habitat in alternative locations as redress for the habitat lost by man-made coastal defences (including from coastal squeeze) or other built interventions, implementing an obligation under the Habitats Directive to both maintain protected site habitat extents and to ensure the continued coherence of the habitat network. This obligation is especially relevant for SMPs that have led to implementation of HTL policies which are expected to be associated with habitat loss (notably due to coastal squeeze). This occurs when an evidence-based options appraisal indicates the alternative options to HTL are less tenable: in these cases, the decision to commit to habitat loss needs to be formally justified following an Imperative Reasons of Overriding Public Interest (IROPI) test. Habitat creation targets are therefore developed to offset the existing or expected habitat losses. Habitat compensation is intended to be delivered in advance of the loss of existing habitat but has also been retrospectively applied to include past losses in Natura2000 areas back to a notional 1994 baseline. In addition, some areas of intertidal habitat creation involve losses of terrestrial/freshwater habitats inland and this needs to be included in the compensation balance. It is also the stated intention of habitat compensation programmes that habitat targets are kept under regular review to include: potential losses identified through further assessments including new monitoring data; the additional consequences from new plans or projects; and updated projected habitat losses based on new climate change projection. However, at present full details of how this review process will be independently validated and implemented are not available.

More than 95% of the habitat created has been in England, and whilst it could possibly be argued that more opportunities exist in this country, our assessment is that this also reflects a greater emphasis on identifying and realising opportunities despite existing barriers, as also concluded by the Sustainable Shores project (Miles and Richardson, 2018). In addition, England, and to a lesser extent Wales, have moved towards formal accounting and reporting of habitat losses and gains, in the context of coastal defences and coastal squeeze, which also provides a clearer indication of progress in risk management compared to Scotland and Northern Ireland, notwithstanding challenges regarding data quality (which are also increasingly recognised through the formal reporting process). Regarding intertidal habitat, just over 50% was created through habitat compensation schemes, whilst the rest was due to initiatives such as shoreline naturalisation or flood protection benefits.

Although these developments, especially in England, are a positive step, they are dwarfed by the scale of UK historic habitat losses on the coastline before the 1990s (ONS, 2016), including more than 8000 ha of intertidal habitat loss since 1945 (>15% of existing habitat; Miles and Richardson, 2018). This has been especially severe in some locations that are especially vulnerable to increased flooding and erosion risk. Current progress indicators based upon target areas to redress habitat losses from coastal squeeze do not incorporate measures of habitat condition and ecological integrity or functionality, nor the loss of habitat outwith SAC/SPA designated areas (Oaten *et al.*, 2018; Pontee *et al.*, 2021). Hence, it is not clear to what degree the habitat compensation has achieved a 'like for like' replacement, or even whether this is even possible. This refers not only to the biodiversity value of the habitat (the UK Biodiversity Action Plan aims for no net loss and to maintain the quality of the resource in terms of species and diversity), but also the multiple ecosystem functions and services that would be provided by healthy, resilient, and adaptive ecosystems, including also by the natural synergies that occur through the mosaic of inter-connected habitats in the coastal zone, rather than each habitat in isolation. This is more likely to happen with the larger, landscape-scale initiatives.

In addition to their biodiversity importance, evidence also continues to become available that managed realignment and associated intertidal habitat creation can have an important role in reducing flood and erosion hazards although the wide variety of site conditions can make generalisations difficult. Recent analysis by Kiesel *et al.* (2020) has shown that scheme features, including breach design and size of realignment site are crucial in alleviating flood risk: for example, an approximate doubling of site size can increase average wave attenuation rates by about 16 times.

Larger-scale examples of realignment include Alkborough Flats where saltmarsh habitat creation was linked with improved flood storage and flood risk alleviation in the Humber estuary. Medmerry is currently the largest managed realignment project on the open coast undertaken in Europe and has provided flood risk management and 183 ha of intertidal habitat. Another noteworthy example is at Steart (Somerset) in the outer Severn Estuary where setback of the defence line and deliberate breaching of previous flood defences has allowed a diverse range of habitat types to be created (183 ha saltmarsh; 40 ha intertidal mudflat; 69 ha transitional brackish habitat; 79 ha coastal grazing marsh; 32 ha of brackish and saline lagoons; 26 ha of freshwater lagoon). Scotland also now has several examples of managed realignment and SEPA have identified opportunity areas for habitat creation and natural flood management. Although there is uncertainty regarding habitat outcomes, analysis at key sites suggests that removal of embankments will allow the intertidal zone to revert to a more natural process of erosion/accretion which can maintain habitat condition (e.g., Freiston Shore: Ni *et al.*, 2014).

Good practice in developing habitat creation schemes is now being produced, as for example with the Restoring Estuarine and Coastal Habitats (REACH) programme led by the Environment Agency. The compensation rationale extends back to habitat lost since the year 1992 but does not cover the changes that occurred before then, which included the loss of intertidal areas to major land reclamation schemes (often large-scale losses), and which have now significantly modified the natural ecohydrological and geomorphological functioning of the coast.

As identified in the CCRA2 Evidence Report, it is important to recognise that habitat restoration or compensatory habitat may not recreate the same biodiversity, resilience, or ecosystem function and services as in the past. This is especially noteworthy as sea-level rise and other marine influences are being accompanied by other climate-related changes, such as temperature and precipitation. Long-term assessment of ecosystem restoration projects is complex because of ecological processes such as succession, particularly in highly dynamic ecosystems such as estuaries (Boerema *et al.*, 2016).

Current progress in habitat creation and compensation can be summarised as follows:

#### 3.18.2.1.2.2 England

In England, the Habitat Compensation Programme (EA, 2018c), estimated 106 ha freshwater grazing marsh, 1021 ha saltmarsh/mudflat and a further 274 ha of other habitats (mainly reedbeds, but which also includes some saltwater habitats) would be lost between the SMP initiation phase (ca.2010) and end of 'epoch 1' (ca.2025) due to coastal protection schemes. These losses have been offset by creating new habitat compensation areas which are reported to be delivering or already delivered a greater area than that projected to be lost in this epoch (EA, 2018c). Since 2000, over 900 ha of inter-tidal saltmarsh and mudflat have been created and a further 300 ha is being developed, therefore current estimates suggest a net gain of 296 ha based upon a 1994 baseline, although this does not include the large-scale losses before that baseline year. In addition, ca. 770 ha of reedbeds and coastal grazing marsh have been created in England since 2011.

Separate targets have been set for each main estuary complex, which are assumed as the minimum habitat needed to begin site recovery for designated sites (Royal Haskoning DHV, 2020). It is also recognised that more monitoring and evaluation is required to facilitate targeting and application of the 'Healthy Estuaries' tool may facilitate this although it requires whole estuary coverage of both LiDAR and bathymetry data.

Regional disparities in habitat creation remain and not all locations show a net gain in themselves, notably because much of the new habitat has been in the Humber estuary. It can also be identified that the primary focus has been intertidal habitat and freshwater marshes, with less emphasis on other habitats (e.g., saline lagoons, shingle features etc.). For vegetated shingle, the extent of losses incurred by the Folkstone to Cliff End Strategy (maximum length 10 km) and for the Dee, Solent, Hamford Water and the Humber remain to be quantified (EA, 2018c) and included in compensation planning at the time of the present CCRA.

A review of the effectiveness of site compensation measures (Morris *et al.*, 2016) has highlighted that more emphasis needs to be placed on the functionality of habitat creation rather than just its extent, and also the need for increasing consistency (including clear success criteria) in the approach to predicting the timescale for compensation to become functionally viable. This study noted that in the majority of cases a time lag occurred between the loss of Natura 2000 habitat and the point where compensation measures have become functionally effective. Monitoring had also largely concentrated on the compensation site, rather than on the whole Natura 2000 site.

#### 3.18.2.1.2.3 Northern Ireland

No equivalent initiative for habitat accounting and compensation has been identified for Northern Ireland, which further confirms an information deficit here when compared to other UK nations.

#### 3.18.2.1.2.4 Scotland

In Scotland, although Dynamic Coast has identified natural assets at risk of coastal erosion, plans to develop a strategic programme of habitat accounting or compensation remain at an early stage and currently no details of total habitat losses and gains are available at national scale through a verified reporting procedure (i.e., equivalent to the habitat compensation programmes reported for England and Wales). Intertidal habitat totalling 72.5 ha has been created to-date in Scotland. Habitat creation schemes at Nigg Bay (25 ha) and Skinflats (11 ha) both aim to redress historic losses from land reclamation, whilst Black Devon Wetlands (28 ha) also aimed to redress future coastal squeeze losses.

#### 3.18.2.1.2.5 Wales

In Wales, the National Habitats Creation Programme has projected habitat losses of 4663 ha by 2105 (assuming continuation of current rates of sea level rise) and is developing a strategy to replace these losses. The programme had created 459 ha habitat to 2018 and is proposed to be on target with plans for an additional 300 ha to offset losses identified within the 1st epoch of SMPs. However, most of the habitat creation has been in the Severn Estuary (elsewhere only 43 ha has been created, of which only ca. 15 ha is considered compensation for coastal squeeze). The available information does not distinguish between different types of habitats lost or created, or whether shingle, dunes and grazing marsh habitats are included. Analysis by Miles and Richardson (2018) also notes that although some estuaries (Dee, Severn) are shared with England, the figures and projections are inconsistent, again pointing to an underlying data issue for the coastal zone. In addition, there are challenges in separating out historic habitat losses from those which occurred since the 1990s when SMPs were implemented (Oaten *et al.*, 2018) and for which the 'no net loss' obligation is only assumed to apply by government.

#### 3.18.2.1.3 Addressing Cross-scale Issues and Climate Change Uncertainty

Forward projections of future habitat losses from coastal squeeze are challenged by multiple uncertainties, and even at present the monitoring of habitat changes associated with coastal squeeze has recognised limitations (Oaten *et al.*, 2018). Therefore, assessment of measures against concepts of 'no net loss' of coastal habitat remains difficult. One notable confounding factor is the influence of 18.6-year lunar nodal cycle on coastal water levels and hence habitat change. Hence, it has been suggested that monitoring needs to take better account of this (Oaten *et al.*, 2018).

A recent reappraisal of evidence has aimed to define a more consistent approach to coastal squeeze for use in SMPs in order to redress previous inconsistencies in how coastal squeeze has been evaluated (Pontee *et al.*, 2021). This report makes a distinction between habitats lost due to coastal defences and those that would have been expected to be lost anyway through inland habitat migration being constrained by steeply rising ground as a form of 'natural' squeeze (notwithstanding that anthropogenic climate change is the primary driver for sea-level rise). Based upon this distinction it is suggested that coastal squeeze losses attributed to coastal defences may have been overestimated, which has implications for habitat compensation obligations, although either way (i.e., defence-related or 'natural' squeeze) the habitat will be lost and the implications for policy responses to maintain and protect coastal biodiversity remain.

The long-term rate of sea-level rise is undoubtedly a key factor in projected losses and gains of priority habitats. Current habitat compensation requirements appear to be assessed based upon continued usage of rather old climate change data (originally from UKCIP98 data) and generic guidance for flood defence and SMPs (PAG3 guidance from the 1990s), rather than the latest data from UKCP18 (EA, 2018c; Oaten *et al.*, 2018). In addition, the plans cannot yet be considered robust when considered against higher projections of sea level rise, as re-emphasised by an increase in median and upper-level projections in UKCP18 data. A more robust response towards ensuring 'no net loss' would aim to create more compensatory habitat to provide 'headroom' to allow for uncertainties in sea level rise projections and other factors such as variability in the actual amount and quality of new habitat created. Furthermore, a more robust response would also consider habitat creation in the wider context of its integration with other habitat and the coherence of the ecological network as a whole. This is unlikely to be successful unless habitat creation initiatives also extend to cover historic losses that occurred before the advent of SMPs.

Further issues arise because habitat losses due to coastal protection structures can also occur in a downcoast position (as inferred in terms of the dominant direction of longshore drift) due to reduced sediment supply from eroded material, or sediment trapping in a specific location (e.g., from groynes or offshore reefs), involving both coarse and fine-grained material. In addition to downcoast intertidal habitat losses, this can affect dune systems from loss of beach sediment supply, and shingle bars. Increased rates of sea-level rise further modify these relationships, but they are yet to be fully incorporated into habitat availability assessments.

As highlighted above, in situ habitat resilience through accretion, or habitat migration due to realignment, can be strongly dependent on sediment supply which if depleted can exacerbate erosion and resultant flooding. Artificial recharge of sediments has now been implemented at several sites to facilitate natural adaptation, including for salt marsh restoration at realignment sites and to redress coastal erosion problems (e.g., at Montrose, east Scotland; or the 'Sand Engine' at Bacton on the Norfolk coast). However, such approaches require cautious identification of licensed sediment source areas in order not to move problems elsewhere.

#### 3.18.2.1.4 Institutional Challenges for Policy Implementation

Across all the UK, the coastal zone involves the interaction of multiple organisations with inter-related responsibilities. In locations where they have been developed, SMPs are intended to integrate national policy with the specific regional and local contexts of different sections of coastline (both biophysical and socioeconomic), but difficulties often occur in reconciling short-term development goals with long-term planning that effectively responds to climate change (Milligan *et al.*, 2009; Coates and Tapsell, 2019). Some stakeholders therefore actively resist a move away from maintaining structural coast defences in their current position, despite increasing evidence of the need for alternative approaches (Esteves and Thomas, 2014; Day *et al.*, 2015) and this can reinforce existing institutional decision-making processes that define hard engineering structures as the 'normal' solution (Harries and Penning-Rowsell, 2011; Challies *et al.*, 2016; van Buuren *et al.*, 2018)). Consequently, there is evidence of typically a default preference for a Hold the Line policy in practice and hence there is still limited implementation of strategies such as managed realignment that

would aim for a more sustainable long-term response (Brown *et al.*, 2017) meaning that coastal defence structures are prioritized over the viability of coastal ecosystems (Cooper *et al.*, 2016). Analysis has also shown that a flexible adaptive approach to setting allowances for sea-level rise in SMPs (and coastal CFMPs), as consistent with the uncertainty in climate change science, has met with resistance in coastal engineering because of the perception that decision making be seen to be based upon a more definitive interpretation of risk (Kuklicke and Demeritt, 2016).

This contradiction between aspirations and actual implementation occurs despite the intention that SMP policies are evidence-based documents. This is sometimes due to inconsistencies in collating and interpreting evidence through the SMP, but more often because of the challenges in reconciling local preferences for the status quo (as expressed by specific stakeholders) with the options as determined by the available evidence that increasingly indicates that the status quo is untenable (Brown *et al.*, 2017; Coates and Tapsell, 2019). Similarly, whilst current aspirations following the SMP Refresh are that SMPs become 'living documents' that are regularly reviewed, in practice there are often institutional barriers (e.g., resource constraints: see House of Commons, Environment, Food and Rural Affairs Committee, 2019) that act against a regular review process. This has meant that SMPs have previously not been systematically assessed in the light of new knowledge or wider policy changes that would often further imply the need for changes in preferred management option.

Nevertheless, it is also appropriate that positive examples should also be highlighted, as with those authorities that have brought together their planning policies under the auspices of Coastal Partnership East (in England) as part of their joint agreement. Similarly, some regional coastal groups have provided an active forum for knowledge exchange across multiple partner organisations which also has benefits for delivering integrated strategies (e.g., Southern Coastal group and SCOPAC for southern England). Similarly, cross-scale interactions are a key focus for the Scottish Coastal Forum which acts as a knowledge exchange mechanism for the five local coastal partnerships in Scotland, and at a more local level for the Pembrokeshire Coastal Forum in Wales which has placed a strong emphasis on community engagement. Further discussion of these contextual issues is provided in the 'Barriers' section (3.18.2.5).

### 3.18 2.2 Effects of Non-government adaptation (N17)

The influence of non-government actions is rather varied depending on local contexts. There are some notable model exemplars in which a long-term strategy has been developed and a transitional plan implemented to facilitate a progressive shift from the current position to this new strategy, typically including a planned shift towards either managed realignment or no further active intervention in order to protect or create new coastal habitat. These examples are most often small-scale and promoted by NGOs together with other interested partners, although the scale of ambition is increasing. A particularly notable lead is being provided by the National Trust, one of the UK's largest landowners, through its 'Shifting Shores' initiative, which establishes a consistent blueprint for adaptive coastal management across all its coastal properties. These positive examples of planned adaptation contrast with those from other local contexts where the approach remains dominantly reactive and for maintaining the status quo, whilst also pushing the difficult decisions into the future (e.g., House of Commons, Environment, Food and Rural Affairs Committee, 2019)



despite the high likelihood of greater long-term consequences from exacerbated climate change risks.

### 3.18.2.3 Barriers preventing adaptation (N17)

Despite some successful examples where new local policies have been developed, there is often considerable inertia in the planning system which favours the status quo, and coastal local authorities are often too under-resourced to take on the significant challenge of developing and implementing new coastal plans that have many interacting complications. In addition, responses are often still localised and dominated by local stakeholder preferences, rather than being set within the regional-scale framework, which was one of the key original objectives of SMPs so that responses at one location do not result in negative impacts being transferred to and exacerbated at other locations in a downcoast situation (Ballinger and Dodds, 2020).

Piecemeal responses can also be a significant barrier. As highlighted most notably for Northern Ireland (Cooper *et al.*, 2016), but also occurring in other parts of the UK (e.g., Brown *et al.*, 2017), shoreline management is still typically considered on a case-by-case basis with little regard to the cumulative effects and the need for a strategic approach to coastal protection. An especially notable barrier for proactive adaptation occurs in response to extreme events, when the recommendations made in SMPs that indicate a transition is required towards a more sustainable coast can in practice be ignored in favour of reinforcing defences in the same location and maintaining a HTL approach as a form of reactive adaptation, therefore perpetuating existing vulnerabilities (Brown *et al.*, 2017). At a more basic level, some parts of the UK, involving most of Scotland and all of Northern Ireland, do not have SMPs or an equivalent strategic procedure that can embed long-term cross-scale planning into local and regional decision-making.

As reported in previous CCRA, the current system for funding coastal protection schemes has also been criticised for also indirectly supporting a bias towards hard engineering schemes to protect built environment or infrastructure assets that can be assigned the largest cost-benefit ratios in monetary terms. This has further contributed to loss of coastal ecosystems from implementation of coastal defence structures (Cooper *et al.*, 2016). These institutional barriers may be at least partly attributable to the inherent challenges in monetising benefits from the natural environment, and also due to the use of engineering design concepts such as ‘standard-of-service’ criteria for coastal protection schemes which are less applicable for dynamic natural habitats and landforms. Emphasis is also placed by government on partnership funding which requires additional sources for co-funding, but there have been significant challenges in engaging private partners in schemes in recent years (House of Commons, Environment, Food and Rural Affairs Committee, 2019).

Current management plans can also be inconsistent and inadequate regarding the multiple benefits that coastal habitat can provide, including for hazard alleviation, amenity value or carbon storage (e.g., Ballinger and Dodds, 2020). Although there is increased recognition of the advantages of nature-based solutions, in practice other socioeconomic factors, typically related to development pressures or preferences of some stakeholders for the status quo, act against this type of initiative at present. For managed realignment schemes, issues related to land ownership and purchase can be difficult to resolve, and the economic case difficult to justify under current funding arrangements. As referred to above, good practice in habitat compensation schemes is being developed (e.g., the

REACH program) but there are often financial barriers to implementing this good practice which is likely to result in a less satisfactory outcome for new habitat schemes.

Another important barrier to effective adaptation is the constraints imposed by inadequate data availability for the coastal zone. A recent report by ONS (2016) identified the following general issues that have hindered natural capital accounting, but which are also very relevant as major impediments regarding progress reporting for adaptation objectives:

- Wide variation in the methodologies, habitat classifications and definitions used to develop accounts for coastal margins, meaning that national summaries vary widely. There is a requirement for improved datasets to be produced using standard habitat classifications and definitions.
- Severe data limitations on the physical extent of coastal margins, except for some protected areas, and also that existing data lack consistency and comparability. Assessments from Northern Ireland are highlighted as particularly lacking.
- The Biodiversity Action Reporting System data for many habitats and countries is based on very outdated surveys.

In operational terms, in our view, another current barrier to strategic-scale intervention is the arbitrary distinction of erosion and flooding hazards rather than to assess them together to develop an integrated approach, as consistent with the original concept of SMPs.

#### 3.18.2.4 Adaptation shortfall (N17)

In conclusion, our assessment is that adaptation is not occurring at a speed and scale to match the climate change risk to coastal habitats and species, both present and future. This is occurring despite government commitments in general towards establishing a sustainable coastline, and an increase in efforts to address this challenge. Priority habitats and species continue to be lost and ecosystem services degraded, although the impacts are variable when related to different policy indicators. Furthermore, in those administrations (England, Wales, and partially for Scotland) that have developed more explicit adaptation commitments through strategic initiatives such as SMPs and habitat compensation schemes, there is not enough evidence at present that these plans have been designed to be robust to climate change, as for example against higher projections of sea-level rise. A related issue is that monitoring of coastal change and of management interventions needs to be made more systematic and consistent to provide the improved quality of information necessary to understand the benefits from adaptation as related to different management options.

The reasons for this adaptation shortfall are also related to the continuing legacy of past decisions, which become increasingly ineffective as the magnitude of climate change increases. Adaptation on the coast involves some very difficult decisions and trade-offs, but our assessment suggests that these decisions may be being pushed into the future rather than addressed now, despite the increased consequences from climate change and rising sea levels. A range of positive examples of planned adaptation do now exist, facilitating both habitat restoration and transition (notably for intertidal habitats), including those led by NGOs and other groups, but these are predominantly local-scale and will be insufficient to fill the national and UK-wide adaptation shortfall as required to

manage risk down to low magnitude levels, both for present and future. Data and evidence limitations at national scale (especially for Northern Ireland) mean confidence in the assessment of adaptation actions with regard to risk management is low. These data limitations should also be addressed as a key component of progress assessment for policy delivery.

### 3.18.2.5 Adaptation Scores (N17)

**Table 3.59** Adaptation Scores for risks and opportunities to coastal species and habitats due to coastal flooding, erosion, and climate factors

Are the risks and opportunities going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	No (Very low confidence)	Partially (Low confidence)	Partially (Low confidence)

### 3.18.3 Benefits of further adaptation action in the next five years (N17)

#### 3.18.3.1 Nature-based Solutions (N17)

As highlighted above, the additional benefits of adaptation are strongly associated with further development of schemes to deliver a sustainable coastline throughout the UK, including through managed realignment as a form of nature-based solution. Additionally, allowing coastal evolution through a decision for ‘no active intervention’ may also enable a more sustainable outcome for the coastal zone. In some circumstances, it may be appropriate to integrate these nature-based responses with structural defences or soft-engineering responses (e.g., sediment nourishment) to combine protection of settlements and infrastructure with protection of the natural environment. The benefits of such actions should include improved recognition of the synergies achieved from restoring and protecting coastal habitats, both for their biodiversity value and for their ecosystem services, notably in providing additional resilience against flood and erosion hazards, and for carbon storage. Setting a clear target for priority habitat creation at national scale would be one policy mechanism to encourage further action, including also monitoring to ensure that good quality habitat is created.

An indicative measure of extended adaptation ambition, including greater adoption of nature-based solutions, has been provided by the CCC Floods study (Sayers *et al.*, 2020) in terms of the reduced flood risk for nature conservation assets (Table 3.60) which can be compared with existing adaptation (Table 3.58) or no further adaptation (Table 3.56). In this context ‘enhanced adaptation’ objectives were defined based upon specific assumptions linked to the scope for managed realignment (see Sayers *et al.*, 2020 for a full description of this adaptation scenario), and following this rationale shows added adaptation benefits are especially realised for England with little difference for Scotland and Northern Ireland (although these country-level differences may also be an outcome of the project assumptions regarding the focus for enhanced adaptation which may be more applicable to some locations). Decisions are also more complex than this in reality because some coastal wetlands (or other habitats) may be able to accommodate additional coastal flooding

whereas for others it may be detrimental, as influenced by key variables such as the extent and duration of saline inundation. In addition, if managed realignment is implemented to set back the defence line and maintain or enhance intertidal habitats then there could be additional benefits in terms of the additional flood and erosion protection provided by those habitats; for example, modelling analysis has indicated that for every kilometre of tidal flat (ranging from high marsh to bare tidal flat), coastal defences can be notionally lowered by 0.84 m–0.67 m when designing for a 1-in-200-year storm event (Zhang *et al.*, 2021). Hence, further and more detailed investigation of these adaptation issues is therefore required to confirm the initial results of Sayers *et al.* (2020), including against a wider range of assumptions and scenarios, and for England the enhanced adaptation commitment implied by the National Flood and Coastal Erosion Management Strategy (EA, 2020; HM Government, 2020).

**Table 3.60** Change in nature conservation assets at significant risk of coastal flooding (frequency of 1-in-75-year or greater) for the 4 nations assuming an extended level of adaptation (Sayers *et al.*, 2020).

ENGLAND					
Assets at significant risk	<b>Baseline (Ha)</b>	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C
Most important habitats exposed to frequent flooding	48,434	28%	36%	36%	60%
Ramsar area in probability bands - Significant	18,649	31%	39%	39%	54%
SAC area in probability bands - Significant	11,647	26%	36%	36%	74%
SPA area in probability bands - Significant	18,139	25%	32%	32%	56%
NORTHERN IRELAND					
Assets at significant risk	<b>Baseline (Ha)</b>	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C
Most important habitats exposed to frequent flooding	1078	18%	33%	38%	55%
Ramsar area in probability bands - Significant	234	24%	44%	51%	73%
SAC area in probability bands - Significant	224	0%	0%	0%	0%
SPA area in probability bands - Significant	621	22%	40%	47%	67%
SCOTLAND					
Assets at significant risk	<b>Baseline (Ha)</b>	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C
Most important habitats exposed to frequent flooding	69,784	2%	4%	4%	5%
Ramsar area in probability bands - Significant	21,784	2%	4%	4%	6%
SAC area in probability bands - Significant	20,338	2%	3%	3%	5%
SPA area in probability bands - Significant	27,663	2%	4%	4%	5%
WALES					
Assets at significant risk	<b>Baseline (Ha)</b>	2050s 2°C	2080s 2°C	2050s 4°C	2080s 4°C
Most important habitats exposed to frequent flooding	40,006	23%	27%	27%	31%
Ramsar area in probability bands - Significant	8,361	32%	38%	38%	44%
SAC area in probability bands - Significant	21,501	21%	25%	25%	28%
SPA area in probability bands - Significant	10,144	18%	22%	22%	26%

### 3.18.3.2 Habitat Creation Opportunities (N17)

To help achieve a higher of ambition for adaptation of coastal habitats and species requires a more detailed systematic survey of habitat opportunities across the UK to update the existing, mainly smaller-scale surveys. In terms of indicative potential, a recent high-level study (Miles and Richardson, 2018) identified 34250 ha of potential intertidal habitat opportunity for the UK, including at priority level 52 potential projects which could contributing 13450 ha of habitat. Obviously, further work is necessary to cross-validate such estimates for their robustness using more detailed source data (e.g. high-resolution topographic data is known to make a substantial difference for low-lying coasts) and against future climate change projections (notably for sea-level rise). In addition, more consistent and robust approaches to record habitat losses and gains are required (including all priority habitats and not confined to designated areas). In England, a broad-scale assessment of potential restoration/recreation sites for intertidal habitat has been developed, which could also provide a basis for more detailed appraisal and implementation at local level (MMO, 2019).

### 3.18.3.3 Integrated Approaches to SMPs and other Plans (N17)

This information also needs to be integrated with current activities to refine and update SMPs (including the SMP Refresh) in order that habitat protection and creation is factored into long-term strategic decision-making. This integration would also be further strengthened by stronger and consistent linkages between SMPs and Flood Risk Management Plans so that the interaction between erosion and flooding hazards are better managed together.

In England, there is a relevant commitment in the new government flood risk policy statement to reform local flood and coastal erosion planning by 2026. It has been suggested through feedback into the CCRA that the wording in both the Flood and Water Management Act 2010 and the Coast Protection Act 1949 (CPA) require adjustment to take into account the need for an integrated approach in the light of climate change impacts. Similar policy adjustments have also been identified for the DAs. Whilst we recognise that current policy developments aspire to deliver a more integrated approach to coastal management, it is not clear how this will overcome the considerable existing barriers identified above, especially when integrating across scales between local, regional and national objectives, and specifically for more sustainable outcomes for the natural environment. In this context, the key transformation challenge remains as policy implementation for a sustainable coastal zone rather than developing high-level policy guidance.

### 3.18.3.4 Monitoring Programmes (N17)

Adaptation would also strongly benefit from continuing and improved coastal monitoring programmes. A shift away from a reliance on hard engineering towards soft interventions, including nature-based solutions, would be reliant on such complementary monitoring initiatives for success. A third phase of the National Network of Regional Coastal Monitoring Programmes is now in progress including asset monitoring for the next 6 years, and there are plans in England for a second national saltmarsh survey. Improved monitoring could also be achieved through increased support for Coastal Observatories (currently 6 regional programmes in England and Wales) including complementary initiatives in Scotland and Northern Ireland.

As recognised by the Dynamic Coast project in Scotland, an upgrade in data quality to 3D time series would provide a step change in understanding the local coastal sediment budget and, crucially, identify areas of sediment loss and gains. This would require whole-coast acquisition of regularly updated 3D time series data of habitat and landform change (e.g., via airborne LiDAR) and better availability of bathymetry and wave data. Further benefits would also be achieved through consistent development of national datasets for natural and artificial coastal flood/erosion defence structures across the UK and for improved understanding and consistent use of coastal sediment budgets in SMPs.

#### 3.18.3.5 Adaptive Management and Adaptation Pathways Approaches (N17)

Ultimately, the strategic direction of SMPs and other coastal plans need to be refined to recognise that future climate change and rates of sea-level rise are inherently uncertain, and hence that flood and erosion management would benefit from an approach that defines multiple adaptation pathways, with the preferred option then related to the magnitude of climate change. The added value of improved monitoring here would be to help steer the right path for shoreline management planning and managed realignment policies based upon up-to-date data. The policy process is beginning to recognise the importance of this adaptability for coastal zone management, but at present, with the exception of very specific examples (e.g., the Thames Estuary 2100 project), there is a lack of examples that we have seen of pathways feeding into strategic coastal plans and of how target outcomes (e.g., habitat creation targets) would be redefined across multiple pathways.

#### 3.18.3.6 Indicative costs and benefits of additional adaptation (N17)

There are some studies which include the impacts (in economic terms) of climate change on some coastal habitats notably wetlands (e.g., see Brown *et al.*, 2011; Schuerch *et al.*, 2018), but these studies do not assess the costs and benefits of adaptation. There are also studies that look at the role of coastal ecosystems for ecosystem-based adaptation, with analysis of costs, cost-effectiveness analysis and cost benefit analysis (Narayan *et al.* 2016; ECONADAPT, 2017; McVittie *et al.*, 2017). However, there is much less information on the costs and benefits of helping coastal species adapt, and there may also be trade-offs with measures to protect the built environment having consequences on species (coastal squeeze). Early low-regret options tend to focus on improved information and monitoring, but there are other measures including possible reinforcement or enlargement of existing measures, e.g., protected areas, buffer zones, as well as restoration of areas or managed realignment, and there are some estimates of restoration costs from previous projects.

#### 3.18.3.2 Overall urgency scores (N17)

As with CCRA2, the urgency assessment for this risk (and unrealised opportunities for habitat creation) is that of 'More Action Needed'. This urgency should be further emphasised by the elevated sea-level rise values in UKCP18 and other projections compared to those underpinning CCRA1 and CCRA2, and by the long lead times expected to restore a sustainable coastline, including for the full range of species, habitats and ecosystem services that nature-based solutions can deliver. A key step in delivering this agenda will be to reinforce shoreline management planning or equivalent strategic planning procedures as implementation mechanisms to bridge between national and local goals based upon a robust interpretation of climate change and coastal science. Habitat restoration and compensation schemes need to be fully aligned with this goal rather than

treated as add-ons, and this will require much stronger emphasis on addressing current implementation barriers at local and regional level.

<b>Table 3.61</b> Urgency Score for Risks and opportunities to coastal species and habitats due to coastal flooding, erosion, and climate factors				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Low	Low/Medium	Medium

### 3.18.4 Looking ahead (N17)

The following information would be useful for CCRA4:

- In addition to sea-level rise, improved assessment of other coastal drivers at local/regional scale including waves and tidal dynamics, and additionally for estuaries to include changes in freshwater inputs (fluvial flows).
- Large-scale opportunity assessment of managed realignment based upon multiple benefits (e.g., using an ecosystem services framework – see section 3.21.3) and a range of sea-level rise scenarios, placing small local schemes in a regional context.
- Assessment of current habitat change for all priority habitats and future habitat change based upon a diverse range of climate change and management scenarios.
- Species and ecosystem function assessments for managed realignment and habitat restoration schemes to monitor ongoing change and progress in terms of their resilience against climate change.
- Integration of the above recommendations with the current SMP Refresh and equivalent SMP processes for all the UK to show the links between evidence, policy, and implementation actions under different adaptation options and pathways (e.g., as defined by different sea-level rise scenarios).
- Further use of the ecosystem services framework to provide stronger links between this chapter and the risks and opportunities defined by other CCRA chapters.



- A unifying issue for all of the above recommendations is the need for improved consistency in monitoring and change assessments (e.g., using a common protocol) to facilitate better transparency in adaptation progress reporting across all the UK.

### 3.19 Risks and opportunities from climate change to landscape character (Risk N18)

- Future changes to landscape character will occur from a range of natural responses to a changing climate including biodiversity, soils, geomorphology, hydrological processes, and coastal processes.
- Landscape character will also be modified by indirect effects of a changing climate, notably through land use change, and there are important interactions with cultural heritage (Chapter 5: Kovats and Brisley, 2021).
- Risks and opportunities from climate change for this topic are assessed as increasing in magnitude from medium (present) to high (future).
- Current adaptation plans for all 4 UK nations for this topic are limited, although there are some important developments at local level that show increasing recognition of the issues and the added value from linking adaptation and landscape change with the Net Zero agenda.
- Nevertheless, assumptions are generally made based upon a single climate change pathway and current plans cannot be considered to be robust against the full range of possible future climate change impacts, especially at the upper end of projections.
- Further development and use of landscape character in planning will help raise awareness and understanding of risks and opportunities of climate change (including interactions with Net Zero pathways), particularly regarding how people relate to landscapes as places to live, work and enjoy.

#### Introduction

This topic is broadly defined to include risks and opportunities relating to landscapes, representing the combined effect of other risks and opportunities from CCRA Chapter 3 with an important link also to the historic environment and cultural heritage (Chapter 5, Risk H11: Kovats and Brisley, 2021). Due to the integrated effect of other risks and opportunities at landscape scale, we assess this topic as increasing in magnitude from medium at present to high in future, especially with higher climate change scenarios. Loss of natural features and phenomena that contribute to landscape character includes both economic impacts and less tangible issues that impact on people's well-being in many diverse ways. Expert opinion has been used predominantly, therefore, in this assessment.

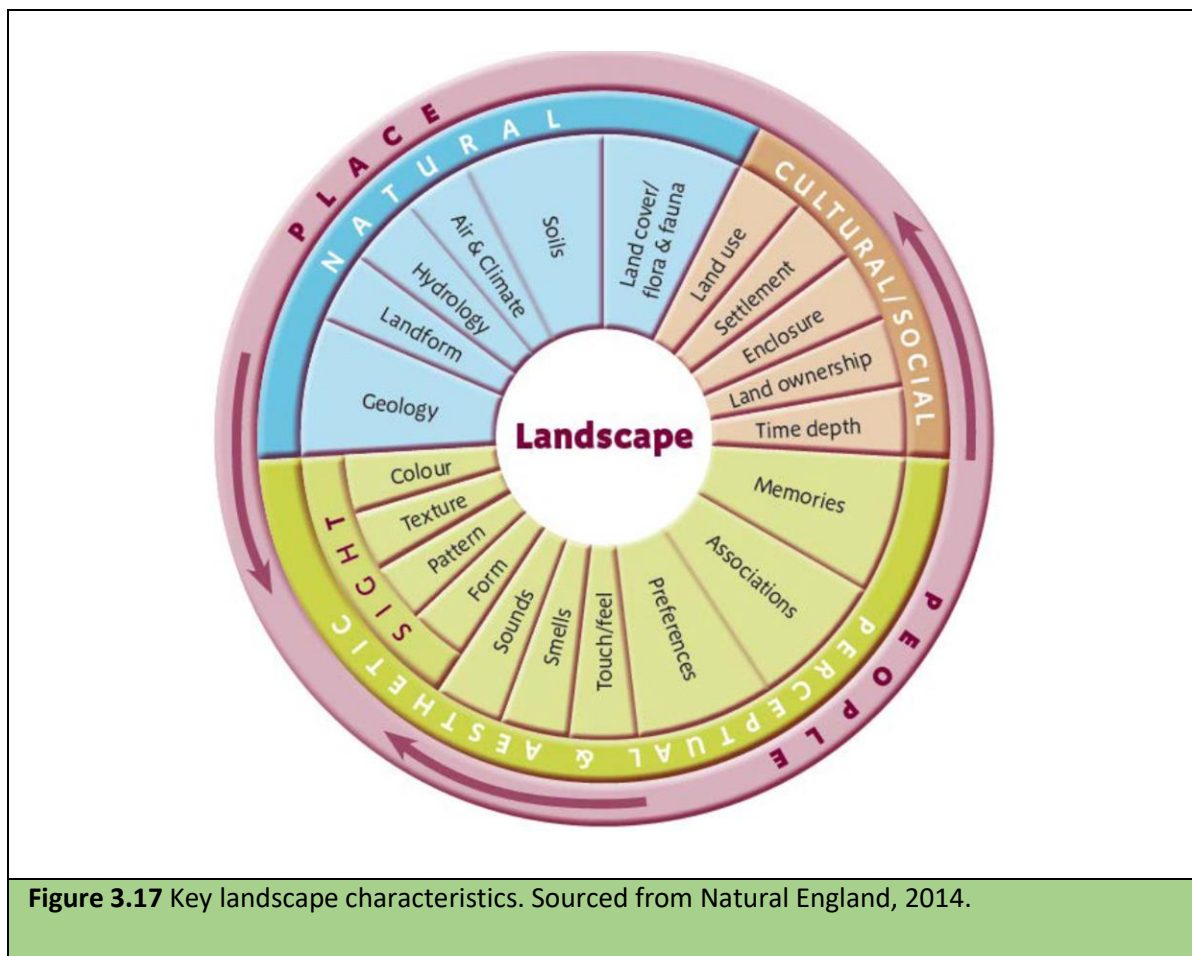
Some important recent initiatives have shown how adaptation could be integrated with landscape concepts, but evidence is still limited. Based upon this current position, we recommend further investigation, trialling, and support for these approaches. This may also have added value in providing a mechanism to bridge between national policies and place-based approaches that

recognise each area's own distinctive landscape assets, whilst also engaging with people who value landscapes in their own individual way, in turn providing a key link between the natural environment and human well-being (Chapter 5: Kovats and Brisley, 2021).

The European Landscape Convention (ratified by the UK) defines a landscape as, *"an area, perceived by people, whose character is the result of the action and interaction of natural and/or human factors"*, putting emphasis on the whole landscape and its multiple values, whilst also recognising its dynamic properties. Landscape character has been formally defined as *"a distinct, recognisable and consistent pattern of elements that occur in a particular type of landscape..... Character makes each part of the landscape distinct and gives each its particular sense of place"* (Natural England, 2014). Landscape functions represent goods and services provided by the landscape as a whole, or key elements within it, and include less tangible properties such as 'a sense of place' that contributes to local identity. Elements contributing either to overall character or specific functions may be recognised as important assets (natural or cultural). Integral to all these definitions is that landscapes, to varying extents, bring together both natural features and cultural elements that represent the interaction of natural processes with the legacy of people (Chapter 5, Risk H11: Kovats and Brisley, 2021 ) in a specific area.

Using broadly similar approaches across the UK, Landscape Character Assessment (LSCA) has then identified and described a wide variety of different character areas. Each of these has its own distinctive characteristics based upon combinations of geology, landform, soils, vegetation, land use, field and settlement patterns (also including the 'seascape' dimensions of coastal areas) and a range of functions that collectively define a multifunctional landscape (Figure 3.17). In addition to their distinctive visual, aesthetic, and historic associations, landscapes also act as the geographic settings for distinctive local produce and customs, notably local food and drink. Some landscapes are also highly valued for their special qualities of 'natural beauty', which is a key legislative characteristic used for designating National Parks (National Parks and Access to the Countryside Act 1949) or Areas of Outstanding Natural Beauty (AONBs: Countryside and Rights of Way Act 2000) and reaffirmed as a key characteristic in the recent Glover Report (Glover *et al.*, 2019). In Scotland, landscape qualities are key components of National Scenic Areas (Planning (Scotland) Act 2006; Town & Country Planning (NSA) (Scotland) Designation Directions 2010) and Scottish Planning Policy 2014 requires appropriate consideration to both designated areas and landscape character. These qualities and features, individually and collectively, may be influenced by climate change (as they have done in the past). The advantage of considering them in a landscape character perspective is the use of a holistic framework and that it can include less tangible characteristics such as sense of place and identity that have been under-represented in climate change decision-making (Adger *et al.*, 2011).

It is very likely that EU-exit will have significant implications for this topic, perhaps most notably through changes in land use that occur as a consequence of modified trade agreements and the transition towards new policy and regulatory frameworks. It is also quite possible that the current Covid-19 pandemic may have ramifications for this risk, such as increased awareness of the value of local landscapes. In both cases, however, we have very limited evidence on how these issues may develop in the future and how they will interact with climate change risks.



### 3.19.1 Current and future level of risk and opportunity (N18)

#### 3.19.1.1 Current risk and opportunity (N18)

This topic is considered in terms of both risks and opportunities because of the varying subjective interpretations of landscape change amongst different people and groups. CCRA2 previously defined this as a topic requiring a 'Watching Brief' based upon a process of monitoring impacts and accounting for climate change in future landscape character assessments. Since then, although little primary research has been published, further developments and a greater recognition of landscape character in related issues allows a more refined assessment to be made of the current status. These developments include the inclusion of aspects of climate change in influencing key landscape elements and their functions, and therefore collectively in modifying landscape character, as recognised by adaptation strategies (see 3.19.2 below) produced through local plans for National Parks, local authorities, NGOs and some other major landowners in the UK.

The impacts of extreme events, such as flooding, drought or storm damage, in addition to incremental climate change such as the influence of climate warming on vegetation patterns, have been recognised in some local landscape assessments. Examples of impacts include major changes in coastal areas due to sea level rise and storm events (Risk N17) that have been associated with

flooding and erosion (e.g., North Norfolk: Land Use Consultants, 2019). Impacts on terrestrial ecosystems and habitats (Risk N1) include changes in drought-prone woodland and downland communities in south-east England (e.g., South Downs National Park, 2020) and the poor flowering of heathlands habitats in both 2018 and 2019 as a consequence of excessively dry conditions in summer 2018 and an increase in heather beetle damage (reported anecdotally from several locations including Exmoor, Shropshire and the North Pennines). For freshwater habitats (Risk N11), warmer temperatures have been associated with an increasing incidence of eutrophication, which degrades functioning and amenity value; related issues have been identified throughout the UK including the Lake District, Loch Leven (Scotland) and Lough Neagh (Northern Ireland). In agricultural landscapes, climate-related changes in land use patterns, such as new cropping systems and livestock housing, have to a varying extent modified the traditional character of these landscapes (Risk N6 and Risk N9), as for example identified in Wales (Berry *et al.*, 2019). Some of these impacts have occurred through the combined effect of climate and land use change.

Landscapes have also been modified by the increased incidence of large-scale wildfires in recent years, notably in 2018, 2019, and 2020 (Belcher *et al.*, 2021; see also Box 3.1 in Introduction), and due to drier conditions (e.g., drought during summer 2018). It is possible that the damage will only be temporary as vegetation becomes re-established but also that the loss is irreversible as the disturbance leads to the development of new ecological communities that are more suited to the changing climate at the site. Nevertheless, these changing conditions may also provide opportunities regarding improved knowledge of past environments and people's relationship with them. For example, the Royal Commission on the Ancient and Historical Monuments of Wales (RCAHMW) identified approximately 100 new historic assets during the severe summer drought of 2018 due to the different soil moisture patterns.

Although there are many studies on individual landscape elements, we still have rather limited evidence on the impacts of climate change across the landscape mosaic as a whole, including how climate has interacted with other (socioeconomic) factors. In addition, we also have limited evidence on how these changes have influenced perceptions of landscapes across different user groups.

An important example of these inter-relationships is the interaction of climate change with traditional land management approaches that are integral to the landscape character of many areas of the UK, and often a unique synergistic combination of the natural environment with cultural heritage. Amongst many noteworthy examples may be highlighted hay meadows, water meadows, coppices and orchards, upland moorland habitat mosaics, and some parklands, which can each have a high landscape and biodiversity value that is maintained by traditional practices. A key component of these land management practices is adaptation, in a generic sense, to changing conditions, including variable weather and climate, but there is rather limited information on how these autonomous adaptation responses are (or are not) adjusting to the climate change occurring now, and the challenges this involves with regard to continuing such practices.

### 3.19.1.2 Future risk and opportunity (N18)

Assessing future change for this topic involves considerable uncertainty because it represents the interaction of several other risks (as described above), strong relationships with the magnitude of climate change and socioeconomic change (including policy goals), and diverse interpretations of risk and opportunity compared to the current landscape and its functions. Landscapes are the dynamic outcome of multiple elements, some of which may be considered more dynamic compared to others, meaning response times to climate change (and other drivers) will vary. Better information on these relationships will be important in influencing managed change as distinct from unmanaged outcomes, although it is also possible that some landscapes are 'left to nature' within a 're-wilding' paradigm to also help better understand the response of natural processes to change. Therefore, although we have improved information from specific landscape locations, large-scale assessment of future landscape change remains at lower confidence, although the evidence does allow some inferences on those at higher likelihood of change (e.g., some upland landscapes, lowland agricultural landscapes, coastal landscapes etc.).

As identified elsewhere in this assessment, future changes to landscape elements will occur from natural responses to a change climate through biodiversity (N1 and N3), soils (N4), hydro-ecological processes (N11 and N13), and coastal processes (N17). Changes will also occur through land management responses to climate change, such as new crops or agricultural intensification (N6 and N9), or more substantial changes in land use (e.g., agriculture to forestry), or in some cases through a planned shift to a previous or new state (e.g., floodplain restoration, managed coastal realignment). In addition, future climate change is very likely to bring an increased risk from pests, pathogens and invasive species (N2, N7, N8, N12 and N16). An assessment of potential changes in the Welsh landscape (LANDMAP) using expert judgment has identified how this could bring about a change in many distinctive landscape mosaics (Berry *et al.*, 2019). For example, the presence of wetlands in the landscape may be significantly modified by drought frequency and agricultural landscapes by new crops and management practices. In landscapes that include woodland as a key feature, the presence and mix of tree species is likely to change, possibly including a reduction in some broadleaved species, such as oak and ash. However, there are notable uncertainties associated with undertaking future predictions due to the interaction of climate change with multiple biophysical factors (ecological, hydrological, geological, geomorphological, pedological) and socioeconomic factors (land use, culture, leisure activities etc.). Possibly more realistically, an assessment framework that explored different future scenario pathways may be a more practical decision framework to investigate the relationship between controllable and less controllable aspects of landscape change, including how they relate to target outcomes and public preferences.

Some landscape changes may be less gradual, such as irreversible changes to vegetation communities following an expected increased incidence of drought. In addition, the prospect of increased frequency and severity of abrupt extreme events such as wildfire also increases the likelihood of some valued landscapes being significantly modified.

An important development since CCRA2 is that some studies are now further developing the practical use of LSCA in a climate change context. In Wales, the LANDMAP study (Berry *et al.*, 2019)

has used a high-level approach to qualitatively assess climate change risks for generic landscape types and the resulting strategic planning implications for specific places and their distinctive characteristics. This also provides a strategic framework for monitoring programmes to better inform actual processes of change rather than generic statements.

Furthermore, more information is becoming available on the geodiversity components of landscape in addition to biodiversity. For example, analysis in Scotland found 80 (8.8%) of the 900 nationally and internationally important geoheritage sites are at 'high' risk from climate change based upon UKCP09 climate data (Wignall *et al.*, 2018). These at-risk features include active soft-sediment coastal and fluvial features, finite Quaternary sediment exposures and landforms in coastal and river locations, active periglacial features, sites with palaeo-environmental records, finite or restricted rock exposures, and fossils.

#### 3.19.1.3 Lock-in (N18)

The primary lock-in risk is associated with a presumption for attempting to maintain landscapes exactly as they are now or to restore them to some historic previous condition, regardless of present and future climate change.

#### 3.19.1.4 Thresholds (N18)

As identified in the other Chapter 3 risks that each contribute to this aggregated risk/opportunity, there are important climate-related thresholds, the crossing of which may produce irreversible landscape change. Important examples of this are changes in semi-natural vegetation (e.g., from blanket bog or heathland to grassland; between woodland types; or between coastal habitats) although these are more usually related to the combination of multiple climate parameters rather than just one in isolation (also including the rate of sea-level rise for coastal landscapes).

#### 3.19.1.5 Cross-cutting risks and inter-dependencies (N18)

This topic acts to integrate many of the other risks in this chapter (depending on landscape context), whilst also having important interdependencies with cultural and historic heritage as recognised through many designated sites. In addition, changes in landscapes can have complex effects on individual and collective well-being, such as through the association between 'sense of place' and identity, as for example recognised in the diagnosis of 'solastalgia'-type negative impacts on people due to loss of cherished landscape features (Cunsolo and Ellis, 2018, Tschakert *et al.*, 2019).

Linkages with cultural heritage and the historic environment also indicate that further use of archaeological evidence could be advantageous in improved understanding of local landscape contexts, especially for understanding variability of risks and risk management through time.

#### 3.19.1.6 Implications of Net Zero (N18)

There are very important landscape-level interactions with the Net Zero agenda, especially as the latter is predicated on major land use changes (e.g., woodland expansion; agricultural

intensification; renewable energy installations) and lifestyle changes (e.g., diet; modes of transport; working patterns including homeworking). Landscapes will therefore be impacted by drivers for change from the biophysical effects of climate factors, and from the socioeconomic effects of both climate change adaptation and mitigation responses, acting together. With regard to landscape character, this presents both risks, especially when the different drivers act against each other, or opportunities when they are more synergistic, as may occur through landscape restoration and rehabilitation.

#### 3.19.1.7 Inequalities (N18)

As noted above, landscape change and modifications of landscape character are important because they represent a key component of the relationship between the natural environment and people, as also associated with cultural benefits and cultural heritage. These relationships are fundamentally subjective and therefore can affect individuals or groups of people in very different ways. In addition, there is increasing research showing that interaction of people with landscapes, or a local greenspace within that landscape (e.g., in an urban area), is beneficial for human well-being and quality of life, and by implication that loss of that interaction can have negative consequences, although relationships are often complex (Capaldi *et al.*, 2015; Wendelboe-Nelson *et al.*, 2019; see also section 3.21.3 and Chapter 5, Kovats and Brisley, 2021). We can therefore assume that changes to landscape character will very likely have implications for addressing societal inequalities, although at present there is very limited evidence that directly engages with this issue.

An important issue to recognise, including in a climate change context, is that all landscapes matter and have their own distinctive qualities, as emphasised by the Landscape Convention statement referenced above. These qualities are therefore not exclusive to designated areas with regard to interactions between climate change and societal inequalities. This needs to be recognised in policy support for inclusion and engagement, especially of local people, across the full range of UK landscapes.

#### 3.19.1.8 Magnitude scores (N18)

Magnitude categories are based on expert judgement as related to existing and expected impacts across the wide diversity of UK landscapes and landscape types (as also informed by other risks in this chapter that aggregate at landscape scale). Landscape character is a descriptive terminology therefore quantification is more constrained for this topic. Risk magnitude is assessed as increasing from medium at present to high in future with the exception of 2050 under the lowest climate projection when the magnitude of change may not be as pronounced. However, confidence is low for all of this assessment due to the limited evidence available, especially when referenced against CCRA risk categories. It should also be noted that here we are assessing climate-related magnitudes of change for landscape features; whether these represent risks or opportunities involves subjective judgements and are therefore not further distinguished.

**Table 3.62** Magnitude score for risks and opportunities from climate change to landscape character

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	Med-High	High	High	High
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Medium	Med-High	High	High	High
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Medium	Med-High	High	High	High
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Medium	Med-High	High	High	High
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

### 3.19.2 Extent to which current adaptation will manage the risk and opportunity (N18)

#### 3.19.2.1 Effects of current adaptation policy and commitments on current and future risks (N18)

##### 3.19.2.1.1 UK-wide

At national scale, there have only been limited further developments of adaptation policy in a landscape context since CCRA2, although the UK is a signatory to the European Landscape Convention. The appropriate national adaptation plans for each administration provide general statements of support and aim to improve awareness, but prefer to highlight positive local case examples rather than set out a national framework for achieving landscape-scale objectives. Guidance is provided by the national conservation agencies on Landscape Character Assessment (LSCA), which is increasingly recognising climate change risks and responses (adaptation and mitigation) (Natural England, 2014; Berry *et al.*, 2019). However, it is difficult to define and assess progress regarding the effectiveness of adaptation policy actions even with regard to the current climate, most notably because there is very limited reporting on progress, such as may be provided using indicators associated with landscape character. For this reason, we cannot currently say whether current adaptation plans for all 4 UK nations are robust against expected future climate change, especially at the upper end of the climate projections (4°C scenario etc.).



#### 3.19.2.1.2 England

The National Planning Policy Framework (NPPF) calls for valued landscapes to be protected and enhanced (NPPF para 109), with the greatest weight being given to conserving landscape and scenic beauty in National Parks and Areas of Outstanding Natural Beauty (AONBs) (para 115). An up-to-date LSCA is also recommended in the NPPF to support planning decisions by local planning authorities. The Landscape Recovery component of the proposed new Environmental Land Management (ELM) scheme (see Risk N1 for more details) has potential to deliver landscape-scale initiatives co-ordinated across multiple land managers for maximum benefit, although this is currently only at policy development stage.

#### 3.19.2.1.3 Northern Ireland

For Northern Ireland a comprehensive assessment of both the 26 regional landscape character areas and the 24 seascape areas identified on the coast has been previously conducted by DAERA. This provides a good reference base from which to assess changes in the key characteristics that define these areas, but the information is yet to be updated based upon current knowledge of climate change risks, such as by using UKCP18 or previous CCRA Evidence Reports. Similarly, plans for designated AONBs are yet to be updated with climate change adaptation strategies.

#### 3.19.2.1.4 Scotland

The second Scottish Climate Change Adaptation Programme (SCCAP2) mentions further development of landscape-scale initiatives, which may be also further facilitated through the place-based approach being further developed through the Land Use Strategy. Notable examples include the Central Scotland Green Network and landscape initiatives being developed in the Cairngorms National Park. NatureScot also intend to deliver a minimum of 15 capital projects across Scotland that improve or create at least 140 hectares of urban green infrastructure. Plans are also being developed to re-appraise climate change effects on landscape character as part of the action plan of collaborative tasks identified by NatureScot and Historic Environment Scotland (HES) through their 2019 joint landscape position statement 'People, Place and Landscape'. The work will review previous work from 2011 and potentially use it as a baseline with initial outputs anticipated in 2021. National Scenic Areas are also an important designation for recognising high-quality landscapes in Scotland and will provide an additional focus for defining local risks and opportunities. An associated initiative 'Building a Fire Resilient Landscape' is intended to promote awareness and changing practices regarding the changing risk from wildfires.

#### 3.19.2.1.5 Wales

The Welsh Government's Planning Policy sets out national land-use planning policies that acknowledge the issues; 'Distinctive and Natural Places' recognises that climate change is likely to have significant impacts on landscape character, historic buildings, local distinctiveness and quality. As noted above, the LANDMAP study (Berry *et al.*, 2019) is being used to develop a strategic framework for considering national-level policy and planning issues and their integration with local planning. Building resilience to climate change at a landscape level is built into SPG guidance in each

National Park, but mostly dates from 2014-15 and is therefore yet to be updated with new information such as from the CCRA2 Evidence Report or UKCP18. Some, but not all, AONBs do include CCRA2 risks in management plans, or aim to do so during an upcoming update phase. At regional level, Climate Ready Gwent is identifying landscape-related multi-partner opportunities to enhance local ecosystem and community resilience in the context of climate adaptation and mitigation. Regarding synergies with the historic environment, the Historic Environment Group (Climate Change subgroup) have led production of a Historic Environment Climate Change Sector Plan that is focused on climate risks to particular landscapes and historic assets in Wales and this has made some use of UKCP18 data.

#### 3.19.2.1.6 Landscape Character Assessment (LCSA) and Geoheritage Assessments

At local government level, use of LSCA in the conventional planning process is being utilised by some planning authorities as a mechanism for further integration of adaptation (and mitigation) decisions into the planning process. Hence, LSCA is used to gauge threats and opportunities to key assets and their functions together with a screening and prioritising of potential adaptation options in an integrative landscape character approach following general national guidance. Prominent examples developing this approach include the South Downs NPA Adaptation Plan, or the Warrington Borough Council climate change strategy. Some of these plans are also being further developed using concepts of ecosystem services and natural capital and are considering adaptation and mitigation initiatives in the context of enhancement of green and blue infrastructure. A prominent example in this context is the Clwydian Range and Dee Valley AONB Natural Beauty guidance on 'Working with a Changing Climate', which has adopted a place-based approach to climate adaptation to raise awareness and understanding of the potential effects of a changing climate within the designated landscape. The same AONB is also providing planning guidance on 'Landscape and Nature Recovery in a Changing Climate'.

In Wales, a follow-on project has further investigated the use of the LANDMAP study (Berry *et al.*, 2019) as a basis for considering both climate change impacts and adaptation and mitigation responses on landscape character and qualities, including as they relate to visual and sensory experience, as associated with 14 landscape types to 2050 (White *et al.*, 2020). The areas include open and wooded uplands and lowlands, coastal edge, built up areas and water. This approach may provide a model for considering how landscape character areas and types can be affected by the changing climate. Nevertheless, methodologies will probably need to be further expanded to include the ramifications of a transition from one landscape character type to another, especially in the context of higher magnitude climate change scenarios and potential threshold effects. For example, the present distribution of agricultural and wooded landscapes will almost inevitably have to change in future (see Risks N6 and Risk N9) in response to climate change as well as other drivers, including the implementation of policies to meet Net Zero.

LCSA also provides a basis to consider landscape sensitivity, which is usually defined as the combination of the susceptibility of change in a specific landscape (i.e., ability to accommodate change without major modification) together with the inherent value of that landscape (in terms of its multiple qualities including visual qualities). Landscape sensitivity is being further developed through guidance in England (Natural England, 2019) and similar guidance is now also being

prepared in Scotland and Wales. In several regards, the landscape sensitivity framework is similar to a risk assessment and therefore sensitivity assessments may allow a further integration of concepts that can inform adaptation decisions, including evaluation of multiple scenarios and adaptation pathways.

Similar methodologies are now also being developed for geoheritage conservation planning which also have important landscape implications (including through recognition of sites of high geodiversity importance, such as landforms or sediment/rock profiles). For example, climate change risk assessment in Scotland has been linked to prioritisation of management actions varying from 'do nothing' to moving boundaries, rescuing excavations, and posterity recording (Wignall *et al.*, 2018).

### 3.19.2.2 Effects of non-Government adaptation (N18)

In addition to local government initiatives, some NGOs are also using the LSCA framework to develop adaptation planning, both as a general strategic approach and for specific locations. Prominent examples include implementation by the National Trust to highlight the anticipated scale of future change and the associated scope to apply nature-based solutions to facilitate adaptation, notably on the coast where managed realignment or a policy of no active intervention implies major shifts in landscape (and seascape) characteristics.

As landscapes are the combined outcome of multiple stakeholders, including both planned and reactive responses, this approach emphasises the added value from a co-ordinated partnership approach to achieve collectively agreed outcomes that cover biodiversity, geodiversity and cultural heritage together. This should include plan development, placemaking and coordinated actions to maximise cross benefits and synergies. An important component of this integrated approach is the advantages of the landscape-based approach to consider risk interactions and cumulative impacts in order to minimise the potential for maladaptation. For example, the 'Living Landscapes' initiative represents a multi-partner approach (led by the Wildlife Trusts) to make space for nature following principles of landscape-scale conservation, including enhanced ecological cohesion and connectivity. Nature Improvement Areas (NIAs) are a network of large-scale initiatives developed in England to improve ecological connectivity and improve biodiversity, typically in areas that have previously experienced habitat degradation; they were launched in 2012 and currently cover just over 100,000 ha in total.

New techniques and revival of previous techniques are being trailed to facilitate restoration of valued landscapes following major disturbances such as wildfires. For example, stakeholder feedback to the CCRA has identified that in Wales, Cadw is testing grassland restoration and management techniques following catastrophic wildfires and severe drought in of 2018, including use of hydro-seeding.

### 3.19.2.3 Barriers preventing adaptation (N18)

Protecting and enhancing landscapes in the face of climate change requires improved awareness of the implications of both current and future climate changes and an inclusive discussion on what is

valued most in different landscape contexts, together with a shared recognition that landscapes are dynamic and some form of managed (or even unmanaged) change cannot be avoided. This is especially needed as some existing adaptation actions can be conflicting in a landscape context. A notable example is that flood/erosion defence schemes may reduce biodiversity value or landscape amenity value; such a relationship has been shown by a national-scale analysis that has indicated that rural house prices in areas with flood defence schemes are reduced by 0.8 to 5% which has been interpreted as dis-amenity value (and potentially flood redirection issues) outweighing perceived benefits from the flood defences (Beltrán *et al.*, 2018). Effective management of landscape change usually requires agreement and co-ordination between multiple stakeholders and this can often impede progress unless an active forum for negotiating issues already exists (e.g., catchment management partnerships or coastal management partnerships). Conserving landscape character and local distinctiveness in the face of external pressures (usually market-driven or policy-based) for significant changes in land use or management (e.g., intensification) is known to be difficult (UNESCO, 2003).

Information on public perception of change in the context of risks and opportunities at landscape level also remains limited and can act as barrier to further development of managed change.

#### 3.19.2.4 Adaptation shortfall (N18)

Despite a recognition by all administrations of the importance of landscape and some positive developments that are mainly for specific locations, it is difficult at present to distinguish effective adaptation responses, and there is very limited reporting on progress beyond awareness raising. At national scale, Wales is the nation that appears to have made most progress in addressing the issues through the strategic development of the LANDMAP project and related initiatives that explicitly include climate change. However, on the basis of the limited evidence available, current adaptation plans for all four UK nations cannot be considered to be robust against expected future climate change with regard to objectives for maintaining or enhancing landscape character, especially at the upper end of the climate projections. Evidence on adaptation actions and outcomes, including how these will interact with socioeconomic drivers and the Net-Zero agenda, is also very limited, hence confidence in assessing the adaptations shortfall is low.

#### 3.19.2.5 Adaptation Scores (N18)

<b>Table 3.63</b> Adaptation Scores for risks and opportunities from climate change to landscape character			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Very Partially (Low confidence)	No (Low confidence)	Very Partially (Low confidence)	Partially (Low confidence)

### 3.19.3 Benefits of further adaptation action in the next five years

Improved collaboration between local and national government in developing a cross-scale planning framework for LSCA that integrates climate change responses (adaptation and mitigation) would be advantageous, as demonstrated by LANDMAP and related projects in Wales. This should also be linked with developments by NGOs and other pioneering organisations. Monitoring is an essential part of the management process to trigger evidence-based interventions. Landscapes also vary strongly in terms of their level of human management, from wild land which may be close to a pristine natural environment to designed landscapes which have been heavily modified and managed to enhance their cultural heritage. It is possible that some designed landscapes (e.g., parks), which are carefully managed, may be used as a controlled environment to test the climate resilience of different species and habitats under different types of management intervention. By contrast, wild land would be more representative of uncontrolled management with a minimum of human intervention. However, many other landscapes would then fall somewhere in the spectrum between these two extremes.

Further investigation of public perceptions is required. Use of 'landscape narratives' may be a useful process to better understand different perception of change to help reveal underlying understandings of nature, climate and human-environment relationships together with how this helps people rationalise different adaptation options (e.g., Köpsel *et al.*, 2017).

#### 3.19.3.1 Indicative costs and benefits of additional adaptation (N18)

This is a very large risk and opportunity, and it is difficult to cover the costs and benefits of adaptation without more detailed and disaggregated analysis. Furthermore, there is very limited published evidence on costs and benefits for this topic. In general terms, enhanced monitoring would be a low-regret option, especially as part of adaptive management. There are an existing set of measures for conservation, landscape restoration, etc. with cost estimates, but it is more difficult to assess the marginal actions needed to address climate change risks.

#### 3.19.3.2 Overall Urgency Scores (N18)

<b>Table 3.64 Urgency Score for risks and opportunities from climate change to landscape character</b>				
	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	Further investigation	Further investigation	Further investigation	Further investigation
<b>Confidence</b>	Low	Low	Low	Low/Medium

Some important recent initiatives have demonstrated how adaptation could be integrated with landscape concepts, especially at local level, which has advantages because this is consistent with the landscape scale and can facilitate enhanced public participation. However, evidence is still

limited, and it is difficult to determine effectiveness of proposed adaptation actions against projected future risks. Based upon this assessment, we recommend 'Further investigation' for this topic to encourage policy support, trialling, and continued knowledge exchange to further implement these approaches throughout the UK and for a wide range of different landscapes.

Adaptation actions include the following:

- Further policy support for existing pioneering approaches linking climate-smart adaptation measures with Net Zero planning in the context of national planning frameworks.
- Clearer national-level guidance and objectives for including adaptation in LSCA and other related assessment tools (e.g., for geoheritage).
- Further development of joint research programmes and strategies linking the natural environment and cultural heritage to define and investigate common adaptation outcomes for specific landscape types and locations.
- Further investigation of the role of traditional land management practices with regard to landscape-scale adaptive management for both the natural environment and cultural heritage together.

#### 3.19.4 Looking ahead (N18)

Further development of LSCA concepts is required at multiple scales (national to local) integrating climate change risks and responses (also integrating adaptation with Net Zero planning) and for the future based upon combined climate change and socioeconomic scenarios. Landscape character could also be further linked to other related frameworks in a landscape-scale approach (e.g., ecosystem services and landscape functions; use of 'soilscapes' to integrate soil functions.)

Further research on relationships between changes in landscape character and subjective well-being would also be very useful. For example, research on the relationships between personal well-being and the impact of invasive species on specific landscapes has identified potential differential impacts on some parts of the community (e.g., emerald ash borer in USA: Jones, 2017).

### 3.20 Cross-cutting Risks (including with other CCRA Chapters)

The risks and opportunities in this chapter have been assessed individually as per the CCRA method, but, as has been noted throughout this chapter, there are a number of factors that affect them and there are many inter-connections between them and risks in other chapters, as well as between policies promoting adaptation and those supporting other agendas including Net Zero. This final section concludes with a consideration of two examples of these: (i) the synergies and trade-offs between adaptation and the Net Zero policy agenda and (ii) the inter-relationships between the risks and opportunities in the natural environment and the services they deliver, as well as with risks and

opportunities in other chapters. They illustrate the benefits of a more systems-based approach, both to the assessment of the risks and opportunities, and to approaches to adaptation in both policy and practice.

### 3.20.1 Synergies and trade-offs between Net Zero and adaptation for the natural environment

Synergies and trade-offs between climate change mitigation and adaptation actions or policies have been investigated (e.g., Berry *et al.*, 2014; Locatelli *et al.*, 2015; Di Gregorio *et al.*, 2017), but less research has been carried out in the context of the Net Zero agenda. A broad range of interactions with Net Zero have been identified for each risk and for some mitigation options suggested for contributing to achieving Net Zero; their key synergies and trade-offs with adaptation are shown in Table 3.65.

<b>Table 3.65</b> Key synergies and trade-offs identified between mitigation and adaptation, including how Net Zero options influence climate adaptation for the natural environment, and how mitigation options are potentially affected by climate change risks and hence require adaptation.				
<b>Mitigation option</b>	<b>Context dependency</b>	<b>Climate risks to effectiveness of mitigation measure</b>	<b>Synergies with adaptation</b>	<b>Trade-offs with adaptation</b>
Woodland and tree planting	Species used; location	Higher temperatures; loss of cold spells; winter waterlogging; drought; wildfire  Pests, pathogens and invasive species	Increased / improved habitat;  climate adapted species;  enhanced landscape connectivity for species migration;  improved water quality;  reduced flood risk;  soil regulation and health	Monocultures and non-natives could fragment native habitats, increase the introduction and/or likelihood of pests, pathogens and INNS (with possible implications for achieving NZ)
Peatland restoration	Location (upland /	Higher temperatures;	Increased / improved habitat;	Possible decreased short-term water supply

	lowland), restoration method	increased seasonal aridity;  increased rainfall intensity;  wildfire	improved water quality;  enhanced landscape connectivity for species migration;  reduced flood risk; reduced wildfire risk	
Bioenergy crops	Crop type / location;  land use replaced	Soil moisture deficits;  water scarcity;  pests and pathogens	Mixed effects on soils	Possible loss of habitats for wildlife;  decreased water quality;  possible loss of land for food production
Low carbon farming (including CH <sub>4</sub> and N <sub>2</sub> O reductions)	Land capability grade / class	Temperature;  precipitation;  humidity;  soil moisture;  CO <sub>2</sub>	Enhanced soil quality;  improved (soil) biodiversity;  improved water quality and quantity;  improved air quality	Potentially with food production if yields are lower
Restoration of marine / coastal habitats	Habitat type / species	Higher sea temperatures;  salinity/ stratification;  CO <sub>2</sub> -driven acidification;  higher sea levels;  storms	Increased / improved habitat;  enhanced species migration;  coastal protection	



In many cases, because of the multifunctionality of the natural environment and dependency on where and how the Net Zero options are implemented, there are often mixed effects on adaptation and the risks. This was particularly noted for woodland planting and bioenergy, where, for example, monoculture plantations are much more vulnerable to climate extremes, such as drought, windblow, and pests, pathogens and INNS. For all of the options more knowledge is needed on their context dependency and the magnitude of their impacts and interactions. Like nature-based solutions, there can be other co-benefits or trade-offs not captured by this analysis, particularly those relating to human health and well-being resulting from improved or increased habitat area or possible opportunities for enjoyment of the natural environment. There is an opportunity to maximise the mitigation-adaptation synergies, and minimise the trade-offs, thus turning the mitigation options into nature-based solutions. The co-benefits from nature-based solutions link to ecosystem services (3.20.2) and to risks in other chapters, such as those relating to water, flooding and food security.

Also considered in this chapter, but currently not part of the Net Zero budgets are the contribution of coastal and marine habitats to climate mitigation. Both sequester “blue” carbon but are susceptible to the impacts of climate change (e.g., from coastal squeeze or ocean acidification – see Risks N14 and N17). There are also potential implications through increased development of coastal and offshore renewable energy resources as part of a Net Zero scenario.

### 3.20.2 Ecosystem Services and the Role of Nature-based Solutions

The natural environment, in addition to its intrinsic value, provides many critical benefits to people and their well-being. In this final section we further highlight implications and interdependencies by synthesising evidence in terms of natural assets and the ecosystem services they provide (also known as ‘nature’s contribution to people’). In doing so, we also reframe the evidence from the individual risks presented above in terms of the implications not only for this chapter but for other CCRA chapters. This perspective aims to focus on key ecosystem services delivered from respective natural assets (recognising that there are many other connections that can exist and that they may be conceptualised in different ways) and to identify not only risks but also the scope and current progress for integrating ecosystem-based approaches into effective climate change responses. Ecosystem-based adaptation and nature-based solutions both aim to recognise and work with (rather than against) the natural resilience and adaptability of the natural environment.

When reframing risks in this format we also aim to highlight important inter-relationships between the ecosystem systems themselves, in addition to goods and benefits provided to people (Figure 3.18). Typically, it is the relationship of the ‘final service’ with people that is most strongly recognised, especially key provisioning services such as food, fibre, and water supply. In addition, especially at a local level, people have diverse cultural interactions with the natural environment that provide less-quantifiable, intangible benefits, such as through sense of place, identity, and amenity value. However, from the perspective of this chapter, we especially aim to recognise and emphasise that the stability and resilience of ecosystems is maintained by a complex array of natural processes, feedbacks, and functions that provide key regulating ecosystem services. These latter services include benefits from hazard risk alleviation (flooding, erosion etc.), but also the functioning natural systems that are integral to our notions of a safe and healthy environment as represented by

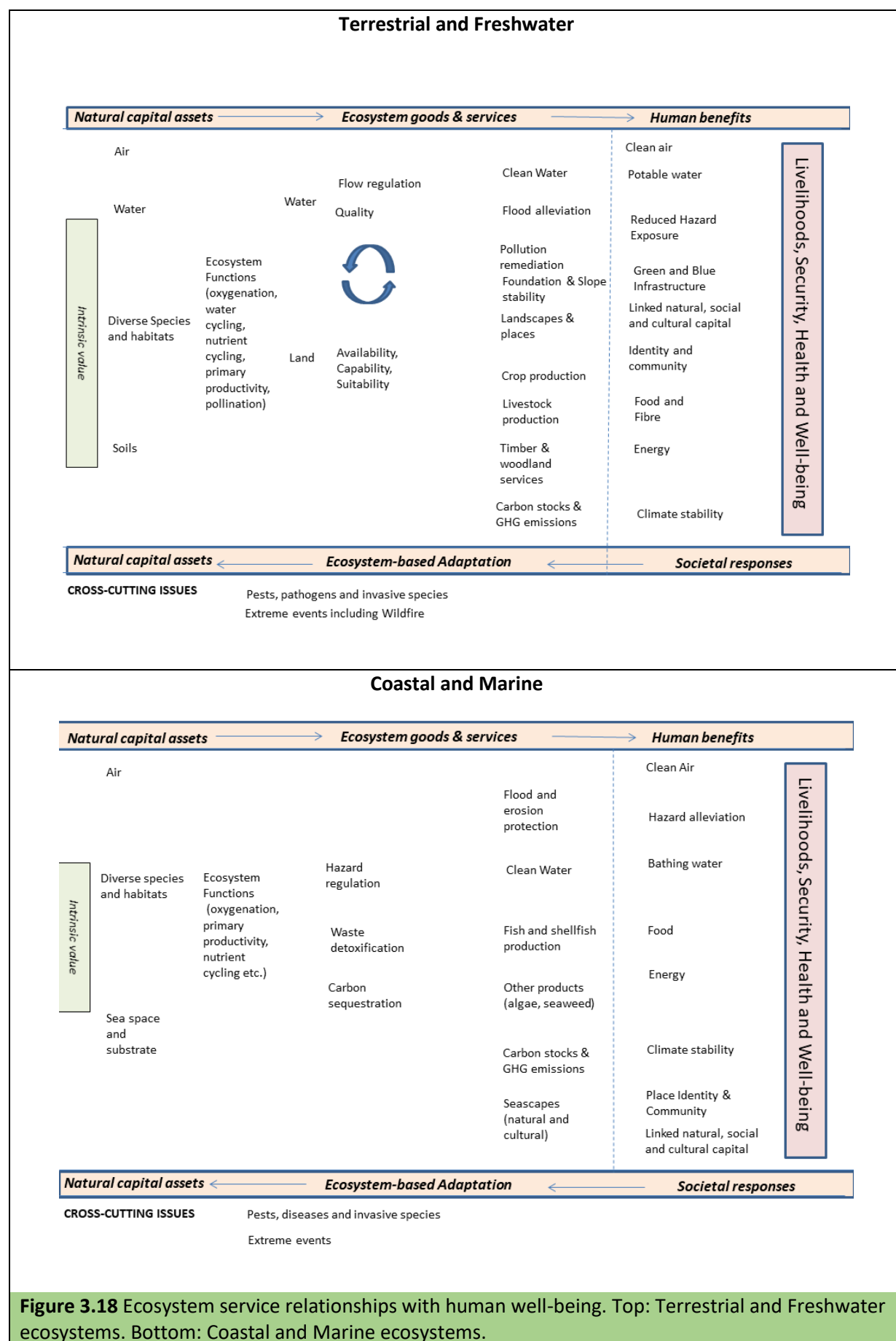
soil quality, water quality, land quality, air quality, or an equable climate, as recognised in international accords, national policy commitments, and societal expectations.

Collectively, these many diverse and interconnected components of the natural environment that contribute to our quality of life can be recognised as Natural Capital. Such terminology can provide a useful analogy to other essential forms of ‘capital’, although as already outlined with unique and sometimes less tangible attributes that challenge attempts at generalisation and simplification (see Dasgupta, 2021). In practice, therefore, the summary findings presented here will require further contextualisation, as, for example, through key ecosystem service relationships both in and between upland and lowland environments, or for urban and rural contexts, or in the context of the coastal zone and the marine environment.

For climate change, one of the primary reasons for concern regarding ecosystem services is the existence of thresholds and even tipping points beyond which ecosystem reorganisation occurs, modifying their functions and services. As we have already highlighted for the 18 individual risk descriptors above, climate can be a key risk factor in crossing these thresholds, and likelihood of threshold exceedance becomes much more pronounced at a 4°C compared to a 2°C world. In reality, risk thresholds may be even closer to the present-day climate than when considered from just a climate driver perspective, as climate change is interacting with other severe environmental co-stressors that reduce overall resilience (e.g., pollution; soil degradation; biodiversity loss).

Although the risks to ecosystem services and hence benefits of more effective risk management may be defined here primarily in terms of a one-way relationship between the natural environment and the other CCRA chapters, we also recognise that for effective adaptation to occur a two-way relationship must be identified and managed. Therefore, effective adaptation in the natural environment is crucially inter-dependent on recognition by other sectors of the mutual benefits from healthy, functioning ecosystems and biodiversity, and for this to be explicitly incorporated into a more joined-up cross-sectoral approach to adaptation responses. This includes requirements for an improved shared understanding of objectives for a sustainable future in the context of a healthy natural environment, cultural heritage, communities, livelihoods, and business functions. Furthermore, emphasis here is placed on UK relationships, but it should be noted that an overly narrow perspective also runs the risk of displacing and degrading natural capital and ecosystem services in other countries. Conversely, if the international flow of goods and services is disrupted (see Chapter 7: Challinor and Benton, 2021), this may place greater pressure on UK natural assets and ecosystem services.

Although ecosystem service relationships are increasingly recognised, there are still many notable gaps in policy implementation in a climate change context. For example, wildfire risk assessments do not yet fully incorporate the importance of protecting natural capital stocks (Belcher *et al.*, 2021) and evaluation of flood risk management plans in Cumbria has noted a lack of inclusion of key ecosystem service relationships in the plans (Huq and Stubbings, 2015). The fundamental importance of understanding and addressing these cross-cutting relationships for developing a more joined-up approach to climate change risk management therefore identifies that they should be a very high priority in forward agendas. This is applicable both in terms of combined government cross-departmental policy action but also in terms of knowledge development and exchange through funded research programmes that are consistent with the scale of the challenge.



### 3.20.3 Implications for Key Ecosystem Service Relationships

Based upon the principles identified above, a series of key ecosystem services relationships (ESRs) can be highlighted for which climate change has important cross-cutting relationships across multiple CCRA risks (as labelled by Chapter identifier).

#### 3.20.3.1 Soil Integrity including Slope Stability (ESR 1)

As assessed for Risk N4, many soils in the UK are in a degraded state and at further increased risk from climate change. This is of major concern because of the fundamental role of soils in the functioning of terrestrial ecosystem systems, in combination with above-ground biodiversity (Risk N1). Soil health is therefore crucial for a broad suite of ecosystem services, including soil fertility for food and fibre production (ESR 5), organic matter for carbon storage (ESR 6), and soil infiltration/filtration processes in naturally regulating water quality (ESR 2) and water flows (ESR 2 and 3). These benefits also extend to the urban environment, including for Sustainable Drainage Systems (SuDS) (ESR 3 and 7). Issues affecting soil structure and slope stability can also have direct negative effects on Infrastructure (Risks I5 and I7) that may be alleviated by enhanced use of the binding properties of plant roots and organic matter. As also noted for Risk N4, increased rainfall intensities from climate change present particular risks for re-mobilisation of spoil heaps and toxic material in contaminated land, and an enhanced role for phytoremediation may therefore have significant benefits for risk reduction.

#### 3.20.3.2 Water Purification and Regulation (ESR 2)

As covered by both Risk N4 and Risk N11, which collectively cover soil-water interactions, climate change is increasing threats to water quality from toxic materials (including pesticides from agriculture), excess nutrients (N and P), and sediments including DOC. These have implications both for drinking water quality (including challenges for treatment plants, notably disinfection by-products such as THCs from DOC) and for bathing water quality (rivers, lakes, and sea, including harmful algal blooms from excess nutrients). The benefits from addressing these risks through nature-based solutions (including improved land management) that enhance raw water quality as a public good is therefore a key ecosystem service that can directly address human health issues highlighted in Chapter 5, Risk H10 (Kovats and Brisley, 2021). In addition, soil-water-vegetation interactions have a key role in regulating water flows which, in addition to the benefits from natural water retention for food/fibre production (ESR 5), can help maintain water supplies (public or private) during drought. The latter also has a related indirect benefit in helping to offset problems that occur during very low flows when dilution of pollutants is further reduced and safe concentration levels for human health exceeded (Risks I6, I8, H10, H11, and B5). Furthermore, natural flow regulation is also of key importance for moderating high flows through flood alleviation benefits (ESR 3) and for Sustainable Drainage Systems (SuDS) (ESR 3 and 7).

#### 3.20.3.3 Fluvial/Pluvial Flood Hazard Alleviation (ESR 3)

Soil-vegetation interactions also modify rainfall-runoff interactions. Therefore, during high flow events, natural soil and vegetation processes and active geomorphological processes can reduce the

speed and quantity of water reaching streams and rivers. This can act to moderate peak flow magnitudes and in turn reduce flood risk. In addition, infiltration processes in healthy soils can reduce surface water flooding in vulnerable topographic locations. Recent increases in severe flood events and the prospects for further increased flood risk from increased precipitation rates in climate change projections (see Chapter 1: Slingo, 2021) has meant that there is a greater interest in using natural flood management (NFM) schemes to help alleviate flood risk. This has been emphasised by indications from recent severe flood events that conventional deterministic and structural approaches to flood prediction and protection have inherent limitations in a non-stationary climate (e.g., Spencer *et al.*, 2018). NFM approaches could have important adaptation benefits for infrastructure, people and the built environment, agricultural land, and businesses (Risks N6, I2, I4, H3, B1, B2: see also Sayers *et al.*, 2020), especially when scaled-up from initial small-scale schemes to catchment scale. However, most of the fluvial environment in the UK is not in a natural functioning state: analysis in England has shown that only 0.5% of the notional fluvial floodplain (as defined by Environment Agency risk maps) is now functional wetland (ca. 3000 ha) (Entwhistle *et al.*, 2019). The same analysis has shown that intensive agriculture on this floodplain zone has increased from around 38% in 1990 to 62% in 2007, although it has since remained relatively static (64%) to 2015 with indications of some arable areas being transformed to pasture.

Increased adoption of NFM requires improved awareness of the need to address existing scientific, institutional and political barriers to its implementation. To date, most of the assessments of NFM have come from small-scale schemes (e.g., ‘leaky dams’) that aim to ‘slow the flow’. The scale effects inherent in ecohydrological processes means these cannot simply be extrapolated to medium or large-scale catchments. In addition, modelling of land use change (e.g., by afforestation) at catchment scale has been used to investigate larger-scale responses. Such modelling again shows considerable benefits from NFM, although it is probable that the largest extreme rainfall events will still result in severe flooding. There has been rather less research on ‘room for the river’ type schemes that aim to create more natural flood storage outwith high risk areas by re-connecting rivers with their floodplains, although some work from other countries indicates considerable benefits from such large-scale approaches if the institutional issues can be overcome (e.g., Molenveld and van Buuren, 2019).

A key issue to recognise for fully-functional NFM schemes (e.g., ‘room for the river’ schemes; wetland creation/restoration; restored floodplain connectivity; riparian/upland woodland) is that they cannot be assessed with the same conventional engineering approaches used for structural defences, such as by inferring a fixed standard-of-service level of protection. Natural systems are inherently adaptable and will naturally adjust from one extreme event to the next (in addition to during more normal periods). In some cases, small-scale hybrid NFM schemes have been developed (e.g., flood retention ponds and bunds) that are both engineered and allow some form of ‘natural’ processes, but adoption of fixed design criteria can remove natural adaptability following each event, especially in the context of the wider catchment response. Therefore, in some catchments a more realistic solution may be a combination of natural and hybrid or structural approaches in order to protect high-risk locations but also retain natural resilience and adaptability. Especially in urban settings, climate change modifications to rainfall frequencies and magnitudes highlight further advantages from natural processes through Sustainable Drainage Systems (SuDS) (see Risk I3 and ESR 7). In all cases, however, the key step for effective adaptation will be to consider rainfall-runoff responses at catchment level and to use integrated catchment management to develop

complementary, proactive approaches, rather than to employ piecemeal, reactive approaches after extreme flood events.

#### 3.20.3.4 Coastal Flood and Erosion Hazard Alleviation (ESR 4)

In Risk N17 we have highlighted the importance of considering erosion and flood risk together from a natural environment perspective, due to them being inter-related processes, but this also has implications for the role of coastal habitats in alleviating flood and erosion risk for infrastructure, people and property, and businesses (Risks I3, H4, B1, B2), especially in hotspot locations (Narayan *et al.*, 2016; Christie *et al.*, 2017). As also noted in Risk N17, in many locations the natural flood and erosion protection is being degraded by coastal squeeze; this is then increasing the threat for interdependent risks in other sectors as they become more reliant on structural interventions that are not practical or cost-effective to maintain, especially with the increased likelihood of higher water levels from sea-level rise (e.g., Cooper *et al.*, 2016; Brown *et al.*, 2017). Shoreline Management Plans are intended to recognise these key interdependencies, and, especially as they are defined based upon natural units defined by coastal cells, to recognise the key role of sediment supply in a sustainable coastline. SMPs include the possibility to define managed realignment or no active intervention for a segment of coast, but as also noted for Risk N17, political and public pressures often act against this happening, undermining the original strategic purpose of SMPs. However, there are some positive examples of a more proactive approach, both at SMP level and also through specific organisations or partnerships that recognise the advantages of working with natural processes in the short-term and longer-term. Similar issues also arise for the further development of NFM approaches on the coast as discussed above in a fluvial context (ESR 3), including the need for an integrated approach throughout the defined coastal cell unit, and where necessary in combination with hybrid schemes or hard engineering structures.

#### 3.20.3.5 Food and Fibre (ESR 5)

Implications of climate change for the food- and fibre-related outputs from agricultural and forestry systems are assessed in Risks N6 and N9 based upon the raw products. In addition to agriculture and forestry businesses, impacts on these farmgate or forest outputs (which have key dependencies with soil and water quality, and biodiversity, such as through pollination) also have implications for businesses in the supply chain that process and distribute food and fibre (Risks B6 and B7), and for food safety (Risk H9). There may also be opportunities here for health and for businesses from enhanced provision of local food, especially where its quality can be assured through environmental quality (Risks H7 and B7). Implications for fisheries (both capture fisheries and aquaculture) are assessed in Risks N14 and N15, and these also have critical links with the health of the wider marine environment, as recognised by increased interest in applying an ecosystem-based approach to fisheries management. Again, the continued sustainability and quality of marine produce is of high importance for suppliers and processors, and for associated coastal communities.

#### 3.20.3.6 Carbon Storage (ESR 6)

Both risks and opportunities for carbon storage are addressed in Risk N5. This is obviously an ecosystem service with global-scale benefits in addition to contributing towards the UK Net Zero commitment. This Chapter further highlights the importance of understanding carbon storage capabilities across all environments and land uses, including coastal and marine systems through

‘blue carbon’. However, Risk N5 also identifies limited progress on assessing the resilience of this key ecosystem service in the context of ongoing climate change, including any planning assumptions for a 2°C or 4°C world. There are many direct and indirect links here with climate change risks, but with increased emphasis on the Net Zero agenda and on climate-related risk disclosure for businesses (Risk B4), interaction of ongoing climate change with plans for validated and verified decarbonisation using ‘natural solutions’ should be especially prominent.

### 3.20.3.7 Green and Blue Infrastructure (GBI) (ESR 7)

For this relationship, we recognise multiple ecosystem services that occur through the presence of greenspace and bluespace (i.e., water features), notably in combination as part of a coherent network of interlinked habitats, and more especially to integrate the benefits of the natural environment for people within urban areas. These multiple benefits include: the natural cooling effect of GBI (through evapotranspiration etc.) compared to built infrastructure, which can have an important role in reducing Urban Heat Island (UHI) effects, and therefore heat stress health issues during heatwaves (Risks H1 and B5); water quantity/quality benefits (ESR 2 and 3); reducing negative air quality issues for human health (Risk H7); and the amenity value or broader cultural and health benefits (ESR 8 and Risk H2) from access to GBI (Doick *et al.*, 2014; Edmondson *et al.*, 2016; Gunawardena *et al.*, 2017; Smithers *et al.*, 2018; Brown and Mijic, 2019). Assessments of these benefits are now being provided for use in integrated planning; for example, average alleviation of UHI effects when aggregated for 11 UK city regions was estimated at between -0.63°C and -0.88°C (depending on land cover type), whilst overall value of urban GBI in these 11 city regions was found to be £166 million annually (Office for National Statistics, 2018). There are also important linkages with the Net Zero agenda including measures to enhance carbon storage and reduce GHGs (Risk N5 and ESR 6). In an adaptation context, there are likely to be considerable added benefits from integrating GBI with other related initiatives in the urban environment (Emmanuel and Loconsole, 2015), notably Sustainable Drainage System (SuDS) schemes. These aim to improve management of surface water drainage through increased use of natural processes, addressing both water quantity (flooding) and water quality (pollution) risks whilst enhancing biodiversity and amenity benefits, especially in the context of local landscapes (Risk N18). This will require that GBI is more fully integrated with conventional approaches to infrastructure and plans to make it more climate-resilient (see Chapter 4: Jaroszowski, Wood and Chapman, 2021).

### 3.20.3.8 Cultural Interactions (ESR 8)

The natural environment is a source for many forms of cultural interaction that contribute to human wellbeing including through inspiration, recreation, recuperation, and identity (Capaldi *et al.*, 2015). In this CCRA chapter we have especially highlighted this relationship through the role of landscapes (and seascapes) and sense of place (risk N18), recognising also the important interaction with cultural heritage (Risk H12). These interactions are complex and typically intangible, meaning they are easily overlooked in a quest for metrics that facilitate easy quantification, but are particularly important at local and regional level (Tschakert *et al.*, 2019). As explained further in Chapter 5 (Kovats and Brisley, 2021), there can be important psychological impacts associated with this relationship, including on mental health and social cohesion across different societal groups and generations, that require further investigation, but also require increased awareness in decision-making (Chiabai *et al.*, 2018). These interactions include both rural and urban areas, as for example

with local landscapes or local food initiatives (e.g., allotments, diverse food crops and ethnic communities; Kell *et al.*, 2018)

### 3.20.3.9 Natural Control of Pests, Pathogens, and INNS (ESR 9)

A narrow utilitarian perspective would consider this issue as primarily defined in terms of an ecosystem 'dis-service' but this misses the importance of the broader issues with regard to the natural environment. In a healthy and fully functioning system, the wide diversity of biotic and abiotic interactions tends to mean that it is difficult for a species that has a detrimental effect for humans to rapidly establish and spread. Biodiversity, therefore, has a key role in controlling spread of pests, pathogens and INNS, and this role extends to having important implications for human health (Risk H8). CCRA1 discussed this 'biodiversity dilution effect' as a working hypothesis and since that time, more evidence has been presented to support the proposition, although more research is also required. Much of the evidence from both a UK and a global perspective is in reality negative, showing that if natural habitats are fragmented by humans and biodiversity is lost, then the spread of pests, pathogens, and INNS becomes more prevalent (as summarised by the recent IPBES (2020) report on pandemic risk). The current Covid-19 pandemic, which evidence suggests originated from zoonotic interactions (as with previous outbreaks such as SARS, MERS, Ebola, avian influenza and swine flu), has only further highlighted the importance of this issue and the role of the natural environment in zoonotic epidemiology (see case study on Covid-19 in Chapter 7: Challinor and Benton, 2021). A particularly important approach that can advance this ecosystem service relationship is Integrated Pest Management: promoting use of more sustainable biological controls to pests and pathogen vectors as an alternative to excessive use of chemical controls that can have an array of long-lasting negative side effects on both the natural environment and human health. This can also include use of research to identify pest and disease resistance in wild ancestors of present-day agricultural, horticultural or forestry varieties, which may be then applied to the susceptible commercial varieties. In addition, further attention to landscape configuration to diagnose existing problems and enhance diversity at multiple levels (from genetic and species level to habitat mosaics) can also act to further enhance natural control measures ('landscape epidemiology' in Plantagenest *et al.*, 2007).

### 3.20.4 Progress on Adaptation for Key Ecosystem Service Relationships

The benefits from ecosystem services and NBS are increasingly recognised in policy frameworks as shown by the 25YEP in England, the Sustainable Land Strategy in Northern Ireland, the second Scottish Climate Change Adaptation Programme (SCCAP2, which uses an ecosystem services framework in defining target outcomes) and the Land Use Strategy in Scotland, and the Future Wales National Development Framework and spatial plan. However, as highlighted above for key ecosystem services relationships, progress on implementation with regard to ecosystem-based adaptation and nature-based solutions remains limited, and often based upon specific case examples, rather than becoming a central and integral component of the adaptation solution space. A key challenge remains in matching prospective solutions to their context, especially for maximising synergies through multiple benefits, and in recognising that natural systems are dynamic and naturally adapt to change (especially based upon their inherent climate sensitivity). This necessitates



a flexible rather than a prescriptive approach and the need for improved regular monitoring to better understand how natural and human systems adapt together.

We conclude by noting the following cross-cutting issues for adaptation of ecosystem services that will be crucial in developing a more coherent relationship between the natural environment and other sectors as the climate continues to change, and to ensure that trade-offs between individual risks are minimised and that synergies are maximised:

- (i) The relationship of ecosystem services with natural processes means they do not usually neatly follow administrative boundaries, requiring a coordinated approach to adaptive management (including both urban and rural authorities). Prominent examples include river catchments and coastal cells for Shoreline Management Plans. The need for improved and integrated planning linking land and sea has also been emphasised by the recent Defra Marine Pioneer project (MMO, 2021).
- (ii) The inter-relationships between ecosystem services requires a cross-cutting approach to avoid overemphasis on addressing risk or opportunities for one service or service type at the expense of others (especially those that may be less tangible or easily quantifiable, such as cultural interactions).
- (iii) More emphasis and research initiatives are required on key thresholds for ecosystem services in the context of climate change, especially regulating services through providing the key link with natural processes, and their implications for safe regulatory limits (water quality, soil quality etc.). Furthermore, the existence of thresholds, feedbacks and other non-linear responses, including from cumulative impacts, means that prediction of future change is inevitably constrained for the natural environment and adaptation responses will need to appropriately recognise this (e.g., through multiple adaptation pathways).
- (iv) The interaction of ecosystem services with both climate change AND socio-economic drivers (e.g., demographics; social attitudes) will be crucial and requires better integration into planning frameworks to help ensure plans are robust and sustainable.
- (v) Caution needs to be applied in applying simple indicators for progress monitoring on ecosystem services that neglect important spatial and temporal variations in the relationship with natural processes (including contextual factors such as land use change and local climates etc.). There are therefore inherent challenges in using simple metrics such as 'area restored', because the outcome may be very variable for different locations. Similarly, concepts of 'no net loss' based on just areal measures do not provide an adequate measure of ecological or hydrological coherence or function. As a precaution against the inevitable uncertainties involved with natural processes and climate change adaptation, measures should really be seeking a considerable 'net gain' at present as an insurance measure to enhance resilience against future uncertainty.
- (vi) Climate change is increasingly going to require permanent change, and hence the management of change is also becoming an increasing component of the required response to address risk and realise opportunities. This transition management will also require a cross-

sectoral approach across multiple ecosystem services, as for example linked to agreed shared outcomes as now being envisioned by long-term policies such as the 25 Year Environment Plan for England, Land Use Strategy for Scotland, Future Wales National Development Framework and spatial plan, or Northern Ireland Sustainable Land Strategy. In this context, it can also be highlighted that the Natural Capital Committee have consistently recommended to the UK Government that natural capital should be viewed as a key component of UK infrastructure. In addition, a report by the National Infrastructure Commission (NIC, 2021) stressed that infrastructure can play a key role in making a positive contribution to the environment, through incorporating a natural capital perspective into infrastructure projects, and to achieve environmental net-gain.

- (vii) In addition to modifying the magnitude of risks, climate change also increases uncertainties. This highlights additional advantages that may be gained from diversification as a generic option for adaptive risk management. From a land use perspective, this implies measures to promote intentional addition of functional biodiversity at multiple spatial and temporal scales in the landscape. In agriculture, increased evidence of diversification approaches is available (e.g., organic amendments, reduced tillage, crop diversification) across a range of ecosystem services whilst not compromising yield (Skaalsveen *et al.*, 2019; Tamburini *et al.*, 2020; Cooper *et al.*, 2021). A similar picture is evident for adaptation in forestry, from genetic to species to landscape-level diversification (Forestry Commission, 2020b).
- (viii) There are very important relationships between ecosystem services and societal inequalities, including in some cases either increased reliance on a healthy natural environment, or difficulties in accessing the benefits from the natural environment. These require further prioritised attention, as without further progress on improving this issue, the additional effects of climate change may lead to exacerbated inequalities. The recent Dasgupta (2021) economic review of the links between natural capital, sustainability and inequality (commissioned by HM Treasury) have further highlighted the need for a fundamental reappraisal and prioritisation of these relationships.
- (ix) A key issue emphasised throughout this chapter, both for assessing changes in risk magnitude and adaptation progress in moderating risk, is the need for improved strategic frameworks for monitoring and evaluation, including to share improved information on responses in the context of 'what works, where, and when'. This requires improved collaboration between academics, practitioners, and policymakers, supported by appropriate funding.

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UK Climate Risk  
Independent  
Assessment (CCRA3)

# Technical Report

## Chapter 4: Infrastructure

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## Key Messages

- **Flooding remains a key risk to infrastructure with the latest climate projections indicating an increased likelihood of heavy precipitation.** There have been a large number of recent high-profile events (e.g. the floods of East Yorkshire in 2020, the Toddbrook Reservoir incident in 2019) which highlight, with increasing confidence, the high magnitude of such risks and their interacting risks and consequences (sections 4.2.1 and 4.3.1). There has been some limited progress across the infrastructure sector in both assessing and adapting to the risk via a suite of flood protection measures (section 4.3.2). However, increasing winter rains will ensure the risk needs sustained management, as will coastal flooding. Revised projections indicate a sustained rise in mean sea levels around the UK (section 4.4.1). The latter is one area in which adaptation pathways are being used extensively (e.g. management of flood risk in the Thames Estuary) and other shoreline management plans (section 4.4.2).
- **Water scarcity in summer remains a concern for supply.** Without adaptation and under a central population growth scenario, the water deficit across the UK by the late 21<sup>st</sup> Century is projected to be approximately 1220 and 2900 Ml/day for pathways to 2°C and 4°C global warming respectively. This equates to the daily water usage of around 8.3 to 19.7 million people (HR Wallingford, 2020. See section 4.9.1). This increase in risk is a combination of population growth and climate change.

To maintain the current levels of risk (to the worst historic drought) in the face of rising population, environmental and climate pressures by the 2050s, would require additional capacity of about 2,700-3,000 Ml/day in England. Further adaptation is likely to be needed; this will more likely be measures that actually reduce demand rather than improve supply (section 4.9.3). Actions to increase supply are also being explored.

- **While significant progress has been made, an adaptation shortfall appears to remain for storms, lightning and high winds in the energy sector.** An increasing dependency on the electricity network (section 4.2.1) means that energy supplies will need to become increasingly resilient to a range of increasing weather and climate risks across the sector (section 4.11.1). In particular, there is an adaptation shortfall to the effects of storms, lightning and high winds (linked to impacts on vegetation), although adaptation to heat and flooding is developing well. Water scarcity will also impact on the energy sector by limiting the cooling of thermal power plants (section 4.10.1) along with uncertain implications for hydroelectric generation (section 4.7.1). There are also considerable uncertainties regarding the effects of the changing future energy mix in the UK in line with Net Zero strategy (e.g. water requirements for the portfolio of Net Zero supply options). In particular, a notable further risk to energy generation is from an increasing reliance on generation of energy from offshore wind which is exposed to storms and high waves (section 4.12.1), although the exact impact of climate change on these phenomena remains uncertain.

- **A changing climate continues to be a problem for the transport sector.** Both Network Rail and national highways agencies have been proactive in implementing adaptation measures on national networks, but sustained action is still required. Significant risks are still posed to railways with respect to flooding (sections 4.3.1 & 4.4.1) and heat (section 4.13.1). On roads, problems are more likely to occur on local roads and smaller schemes (section 4.13.3) and indeed, there is an underlying need to assess the impact of single points of failure more broadly (e.g. bridges (section 4.5.1), earthworks (section 4.6.1) and subsidence (section 4.8.1)). Often a paucity of data is restricting progress in these areas.
- **The systems nature of infrastructure means that any unmitigated risk has the potential to have a propagating impact across the network or lead to cascading failures across multiple networks.** The consequences of cascading risks cause far-reaching social and economic disruption beyond the initial impact. Extensive research is still required into cascading and interacting risks with high profile case studies (e.g. flooding at Stansted Airport in 2013, the impacts of Storm Desmond in Lancaster in 2015) providing increasingly high confidence in the significant magnitude of the impacts (section 4.2.1). This is set to increase with climate change as the individual costs associated with impacts on each network become compounded. The increasing reliance on electricity (section 4.2.2) and Information and Communications Technology (ICT) (section 4.14.1) both represent key areas needing attention. For the latter, there remains a lack of publicly available information to ascertain the true scale of any vulnerabilities in the sector (section 4.14.2).
- **Current national planning policies for infrastructure differ in the extent to which climate impacts and adaptation are addressed.** For new major infrastructure the 2017 update to EIA regulations in England, Scotland, Wales and Northern Ireland, includes a requirement to assess the infrastructure's vulnerability to climate change, however it is not clear how comprehensive these assessments are in practice. Flood risks are also considered at the planning stage. There are fewer requirements for existing infrastructure to adapt to climate change. Some sectors have well-developed plans while other sectors are less well organised or have no coordinating body. Overall, there is a need for a coordinated, cross sectoral review of design codes and standards, climate risk guidance, inspections and maintenance guidance, and wider relevant industry guidance on risk management to incorporate the latest understanding of climate impacts.

Table 4.1 summarises the urgency scores for the 13 risks to UK infrastructure from climate change, using the urgency scoring system described in Chapter 2 (Watkiss and Betts, 2021). The CCRA3 list of risks and opportunities, developed in consultation with stakeholders, did not include any opportunities for UK infrastructure from climate change.

**Table 4.1:** Urgency scores for risks to Infrastructure

Risk number	Risk description	Urgency scores			
		England	Northern Ireland	Scotland	Wales
I1	Risks to infrastructure networks (water, energy, transport, ICT) from cascading failures	More action needed (Medium confidence)	More action needed (Medium confidence)	More action needed (Medium confidence)	More action needed (Medium confidence)
I2	Risks to infrastructure services from river and surface water flooding	More action needed (Medium confidence)	More action needed (Medium confidence)	More action needed (Medium confidence)	More action needed (Medium confidence)
I3	Risks to infrastructure services from coastal flooding and erosion	Further investigation (Medium confidence)	Further investigation (Medium confidence)	Further investigation (Medium confidence)	Further investigation (Medium confidence)
I4	Risks to bridges and pipelines from flooding and erosion	Further investigation (Low confidence)	Further investigation (Low confidence)	Further investigation (Low confidence)	Further investigation (Low confidence)
I5	Risks to transport networks from slope and embankment failure	More action needed (Low confidence)	More action needed (Low confidence)	More action needed (Low confidence)	More action needed (Low confidence)
I6	Risks to hydroelectric generation from low or high river flows	Further investigation (Low confidence)	Watching brief (Low confidence)	Further investigation (Low confidence)	Further investigation (Low confidence)
I7	Risks to subterranean and surface infrastructure from subsidence	Further investigation (Low confidence)	Further investigation (Low confidence)	Further investigation (Low confidence)	Further investigation (Low confidence)

I8	Risks to public water supplies from reduced water availability	More action needed (Medium confidence)	Sustain current action (Medium confidence)	Sustain current action (Medium confidence)	Sustain current action (Medium confidence)
I9	Risks to energy generation from reduced water availability	Further investigation (Medium confidence)	Watching brief (Medium confidence)	Watching brief (Medium confidence)	Watching brief (Medium confidence)
I10	Risks to energy from high and low temperatures, high winds and lightning	Further investigation (High confidence)	Further investigation (High confidence)	Further investigation (High confidence)	Further investigation (High confidence)
I11	Risks to offshore infrastructure from storms and high waves	Sustain current action (Medium confidence)	Sustain current action (Medium confidence)	Sustain current action (Medium confidence)	Sustain current action (Medium confidence)
I12	Risks to transport from high and low temperatures, high winds and lightning	More action needed (Medium confidence)	More action needed (Medium confidence)	More action needed (Medium confidence)	More action needed (Medium confidence)
I13	Risks to digital from high and low temperatures, high winds and lightning	Further Investigation (Low confidence)	Further Investigation (Low confidence)	Further Investigation (Low confidence)	Further Investigation (Low confidence)

## 4.1. Introduction

### 4.1.1 Scope of Chapter

This chapter assesses the climate-related risks and opportunities to infrastructure, primarily focussing on the ‘economic grey infrastructure’ that provides services such as heating, lighting, mobility, fresh water and sanitation to society, aligned with the remit of the National Infrastructure Commission (NIC). Green infrastructure is beyond the scope of this chapter but is included where appropriate as an adaptation measure. The chapter builds extensively on the equivalent chapter in the second Climate Change Risk Assessment (Dawson *et al.*, 2016) by using new evidence, including (where possible) the latest generation of climate scenarios, to update our understanding of previously identified climate risks and the role of current and future adaptation in the sector. The

Introduction Chapter to this report outlines the process and role of Government in choosing the list of risks and opportunities that have been considered here and in the other chapters. This list was provided to the authors by the CCRA Project Board (Customer).

Risks to current infrastructure have recently been systematically assessed through the NIC (2020). However, the scope of the NIC report covers all hazards, which meant that the specific impacts of climate were not considered in detail. The focus here is on the key risks to infrastructure previously identified from CCRA2, as well as the potential for the interaction of risks with other sectors. Following CCRA2, the descriptors to focus on have been combined and subsequently reviewed and approved by Central Government. The result is 13 indicators for infrastructure (Table 4.1) which will individually be covered in the chapter.

Our society and economies are heavily reliant on infrastructure to function effectively and it is a priority area of investment by the UK government (see Box 4.1). The *National Infrastructure Plan* underpins the co-ordinated delivery of major infrastructure in the UK (although with application for devolved administrations) but currently pays little consideration to climate change. However, recent developments in this area are significant. £640 billion of gross capital investment in infrastructure before 2024-25 was committed in the 2020 Spending Review with a new *National Infrastructure Strategy*. This follows the publication of the first *National Infrastructure Assessment* in 2018 (NIC, 2018a) which included a number of climate change related recommendations such as national flood resilience standards and a plan to enable the water sector to meet changing supply and demand in 2050. This has subsequently led to the recently published *Resilience Study by the National Infrastructure Commission* (2020).

### Box 4.1: Socio-economic scenarios and infrastructure

Social, cultural and economic trends are highly relevant to the future risks of climate change, and strongly influence future magnitude through changes in exposure and vulnerability (see Chapter 2: Watkiss and Betts, 2021). They will also influence adaptation, including the capacity and resources of individuals, organisations and infrastructure operators to act. Cultural and socio-economic factors can act together as risk multipliers exacerbating the impacts associated with disruptions to infrastructure services caused by climate change, although for some cases, these factors can reduce vulnerability and thus dampen the overall impact.

The CCC commissioned a new consistent set of UK socioeconomic projections from Cambridge Econometrics (Cambridge Econometrics, 2019) as one of the CCRA3 research projects.

These include projections of population growth, population ageing, and migration (internal migration and immigration), presented in Chapter 5 (Kovats and Brisley, 2021). The central scenario assumes that the UK population grows at a steady pace, increasing by over 17 million (compared to 2016), to reach a total population of almost 83 million in 2100. This rising population will likely increase the demand for infrastructure services.

The Cambridge Econometrics (2019) projections provide central, low and high estimates for total GDP (£ millions, real) and percentage growth (from the previous year), based on estimates from the Office for Budget Responsibility (OBR). The Central scenario envisages a GDP annual growth rate for the UK of about 1.6% from 2018 to 2028 and an acceleration with GDP expected to grow by 2.2% per annum from 2029 onwards (through to 2100). The increase in economic growth will also increase infrastructure needs. This means there will be a large increase in the value at risk, in

terms of the infrastructure assets, service levels, etc., which increases the potential exposure to risk (though future economic growth could provide additional resources to address these risks). The socio-economic study also projected gross value added (GVA), employment and labour productivity, all of which are important for the infrastructure needs associated with different sectors. In the Central scenario all sectors experience a similar growth pattern based on the Central GDP growth rates.

There are a very large number of other socio-economic and cultural trends that could have a large influence on demand for services and thus infrastructure. Some of the more important will include the drive towards digitalisation, change to the work environment (noting the shift towards home working from COVID-19), changes in how leisure time is used (particularly regarding travel distances and mode) etc., as well as long-term policy shifts. COVID-19, in particular, has the potential to result in a significant policy change in terms of infrastructure. Although the UK government announced a £640bn investment in infrastructure in the March 2020 budget, additional investment in large infrastructure projects is likely as the UK and the devolved nations seek to rebuild their economies following the pandemic. This will provide opportunities to enhance adaptive capacity in both new and existing infrastructure.

All proposed investments will need to be critically evaluated through a Net Zero lens as the UK government has adopted a Net Zero target through a revision to the 2008 Climate Act (such that the net UK carbon account for the year 2050 is at least 100% lower than the 1990 baseline). The Scottish Government committed to a target of net-zero emissions of all greenhouse gases by 2045 (Scottish Government, 2019a), with the Infrastructure Commission for Scotland placing inclusive net-zero carbon economy at the core of its 30-year vision (Infrastructure Commission for Scotland, 2020). The Welsh Government has announced a 95% reduction in greenhouse gas emissions by 2050 with an ambition to reach Net Zero (Welsh Government, 2019a). This will impact upon the type of infrastructure the UK will be reliant upon in 2050 as well its role within the wider economy and society (see Box 4.2).

#### **Box 4.2: Implications of Net Zero for Infrastructure**

Following the Paris Agreement, the UK and the devolved nations have committed to achieving 'Net Zero'. However, Net Zero is only going to be achieved if clear policies are rapidly put into place to meet the ambitious targets set. Net Zero has implications across all sectors included in this risk assessment as rapid and significant changes will be required. The infrastructure sector is no different and as a significant contributor to UK greenhouse gas emissions, Net Zero will have major implications for the sector. However, at the time of writing, there is no detailed Government policy on how Net Zero will be achieved, and thus there is limited information on what exactly Net Zero will mean for infrastructure. The Climate Change Committee has published a detailed analysis that presents potential pathways to Net Zero for each sector of the economy (CCC, 2019a). It presents scenarios that illustrate the ways in which extensive decarbonisation of the UK economy could occur, by 2050, to demonstrate that a Net Zero emissions target by 2050 is achievable. However, this includes alternative approaches, and the actual pathways to achieve this are still in development and subsequently a long way from actual policy. Regardless of the route taken to achieve Net Zero, there will be implications for the infrastructure considered in this chapter, and interactions (potential positive or negative influences) with many of the climate risks detailed in this chapter. In particular, the anticipated infrastructure transformation in response to



delivering Net Zero goals will encompass significant changes in energy generation and transport, detailed in Box 4.2 Table 1.

**Box 4.2 Table 1:** Potential change associated with Net Zero and implications for UK infrastructure risk

Sector	Risk affected	Examples of changes associated with Net Zero	Implications for UK infrastructure risk
Transport	I1, I2, I5, I12, I13	<ul style="list-style-type: none"> <li>• Electrification of rail and road transport (electric vehicles) including smart charging infrastructure.</li> <li>• Use of alternative fuels. Hydrogen for Rail; low carbon alternatives such as biokerosene for Aviation.</li> <li>• Increased active travel (walking, cycling etc.)</li> <li>• Increased use of public transport.</li> <li>• Increased use of blue infrastructure (e.g., London Blue Ribbon Network)</li> </ul>	<ul style="list-style-type: none"> <li>• Increased reliance on electricity and ICT with associated potential for cascading risks from weather-related damage and disruption to these infrastructures.</li> <li>• New flood risks to new infrastructure (e.g. electric vehicle charge points)</li> <li>• As yet unassessed risks associated with new infrastructure (e.g. hydrogen production, distribution and storage)</li> <li>• Health and safety risks to increased numbers of cyclists and pedestrians from extreme weather.</li> </ul>
Land Use	I2	<ul style="list-style-type: none"> <li>• Afforestation</li> </ul> <p>Changes in farming practices (e.g. low carbon / restoring peatlands)</p>	<ul style="list-style-type: none"> <li>• Potential to reduce infrastructure flood risk management and reduce extreme river flows and their impact on hydropower output (although afforestation is also vulnerable to droughts)</li> <li>• Conversely, flood risk could increase due to</li> </ul>

			increased debris in rivers.
Energy and Water Supply	I1, I3, I8, I9, I10, I11, I13	<ul style="list-style-type: none"> <li>• Doubling or potential quadrupling of low carbon electricity needed to meet demand from other sectors incl. electrolysis (BEIS, 2020a). Rising from ~300 TWh/year in 2017 to 600 TWh/year under the CCC Further Ambition Scenario with potential for further electrification up to 1300 TWh/year (CCC, 2019a, Figure 2.3)</li> <li>• Increased use of renewables: wind, solar, bioenergy with carbon capture and storage (BECCS)</li> <li>• Development of a hydrogen industry.</li> <li>• Increased development of bioenergy supply chains.</li> <li>• Smarter control systems to improve efficiencies.</li> <li>• Reductions in the demand for fossil fuels.</li> <li>• Changes in water demand due to a changing energy mix.</li> </ul>	<ul style="list-style-type: none"> <li>• Increased reliance upon electricity supply increases the consequences of power outages.</li> <li>• Uncertain projections for future wind generation.</li> <li>• Increased significance of loss of offshore infrastructure to electricity supply.</li> <li>• Increased requirements for water for Carbon Capture and Storage (CCS) and hydrogen (H<sub>2</sub>) production increases vulnerability to water restrictions or coastal erosion and sea level rise if they are sited on the coast.</li> <li>• Bioenergy crops can be impacted by drought, resulting in undersupply.</li> <li>• Changes in the spatial distribution of supply to accommodate greater renewable generation.</li> <li>• Increased dependencies (e.g. on ICT) makes cascade failures to other networks more probable.</li> <li>• Changes in water quantity and distribution needs to accommodate a changing energy mix.</li> </ul>

Overall, Net Zero will change the profile of risk. It will underpin the types of new infrastructure to be built, how and to what extent existing infrastructure is used in the future, decisions on adaptation solutions, and offer opportunities to build in resilience to climate impacts from the outset. It is also highlighted that the changing risks outlined in this report may affect the design of the Net Zero economy as it is important to plan the Net Zero transition so that it operates effectively and efficiently in the future climate, not the climate experienced in the recent past. In the context of this risk assessment, it is too early to provide an evidence-based analysis of how the risk profile will change. Instead implications of Net Zero are provided, where relevant, to provide an indication of whether the policy increases or decreases the risk and also whether climate change will make Net Zero harder or easier to achieve.

#### 4.1.2 The challenges of assessing climate risks to infrastructure

The transport, energy, ICT and water sectors are all fundamental to day-to-day life, yet *all* regularly face weather-related challenges. The nature of the future risk remains similar to previous risk assessments, but the latest climate change scenarios (UKCP18) do indicate significant differences in climate extremes that need to be taken into account. These are summarised in Chapter 1 (Slingo, 2021) and underpin the evidence in this chapter wherever possible. It also highlights the need to increasingly consider low likelihood, high impact events for the infrastructure network (see Box 4.3)

##### **Box 4.3: Low Likelihood, High Impact scenarios and Infrastructure**

Chapter 1 (Slingo, 2021) has illustrated how there is now increasing evidence towards significant changes in future extremes of temperature and rainfall, as well as a changing evidence base in Earth system instabilities. Such changes could result in ‘tipping points’ being passed, leading to high impact outcomes across the risk indicators covered in this chapter. If scenarios or events which are unlikely but more extreme do occur, they would then be more likely to trigger cascade impacts (I1) via interacting risks (see Box 4.4).

The evidence base for such outcomes remains limited, although some examples have been explored. For example, Yesudian and Dawson (2021) assessed the risk to airports worldwide from scenarios of sea level rise from Jevrajeva *et al.* (2018), which are higher than those in UKCP18.

These scenarios considered much larger contributions of ice loss from Antarctica than in the UKCP18 projections (De Conto and Pollard, 2016), which other work suggests may overestimate sea level rise risks this century (Edwards *et al.*, 2019). 1,238 airports were defined as being in the Low Elevation Coastal Zone (the area along the coast that is less than 10 m above sea level). Globally, the risk of disruption was projected to increase by a factor of 17–69 by 2100, depending on the rate of mean sea-level rise. A projected global mean sea level rise of 0.62 m by 2100 would place 100 airports around the world below mean sea level. While such a rise is almost the median projection for 2°C global warming by 2100 in that study, in UKCP18 it is at the upper end of the projected range for 2°C global warming by 2100 and the median for 4°C global warming by 2100 (see Chapter 1: Slingo, 2021). Yesudian and Dawson (2021) highlight that airports already benefit

from substantial flood protection that reduces present risk by a factor of 23 and to maintain risk in 2100 at current levels could cost up to \$57bn. Within the UK, London City airport ranked in the global top 20 by risk in 2100 for a 1.8 m global mean sea-level rise by 2100, which is the 95<sup>th</sup> percentile in the RCP8.5 scenarios considered by Yesudian and Dawson (2021) but substantially above the RCP8.5 95<sup>th</sup> percentile in UKCP18 (Palmer *et al.*, 2018).

Some changes, such as shifts in the Atlantic jet stream which underpins the UK's weather and storminess in general, can be sudden and cause unprecedented impacts. This was seen in 2020 when compound failures from two extreme storms in quick succession (Storms Ciara and Dennis) caused severe flood damage, with the impacts of the second storm felt even greater as it hindered clean-up operations from the first.

Weather and climate both impact on infrastructure performance and manifest in a variety of ways, but often lead to costly disruption or, in more severe cases, loss of service entirely. This has significant implications, not just for economic activity, but societal equity, health, and well-being more generally. However, there exists a continual trade-off between the cost of risk management versus the level of residual risk. Following NIC (2020), work is only just beginning on producing clear guidelines detailing the acceptability of loss of performance by the public, and indeed the willingness of the public to accept reduced levels of service when faced with an increasingly challenging operational environment (e.g. a climate emergency) in order to base such decisions. However, some sectors have begun this process. For example, as a starting point, water utility companies have surveyed the public to ascertain willingness to pay for investment in long-term adaptation measures.

A key consideration, particularly in light of the proposed investments, is the lifespan of infrastructure assets. Infrastructure is (mostly) designed for longevity and means that much of the infrastructure in existence today will be in place for the remainder of the century. Hence, there is a need to consider implications both for existing (potentially retrofitted) and new infrastructure. Climate change is actively considered when planning major new energy, transport, waste water and water projects under guidance from the UK Government's National Policy Statements, however guidance under the National Planning Policy Framework and Planning Guidance for smaller projects only considers flood risks and does not ensure other climate risks are considered (CCC, 2019b). For existing assets, adapting to climate change presents operators and owners with a challenge of coalescing and reconciling (where possible) actions across a range of aging assets, with differing design codes, environmental exposure, usage and maintenance regimes – all of which combine to determine how an asset may respond to a changing climate. Work is ongoing to introduce standards across Europe (see ISO 14090/14091) where the UK is represented by members of the Infrastructure Operators Adaptation Forum, but there is a sense that the inclusion of climate adaptation remains in its infancy. The CEN/CENELEC Coordination Group on Climate Change Adaptation (ACC-CG) has, as part of an EC mandate started in 2014, been steering the revision of 13 European standards to include adaptation to climate change. Translation of ISO 14090 into British Standards is also underway with a roadmap to be produced in due course. The British Standards Institution is currently developing BS 8631, due for publication by mid-2021, that provides guidance on developing and applying adaptation pathways to climate change adaptation planning and decision-making. However, it is highlighted that even when there is some guidance, designing climate-smart infrastructure in practice is extremely challenging. This is partly because of the high uncertainty around the future

climate (see Chapter 1: Slingo, 2021), and also because of the need to trade-off up-front costs versus long-term adaptation benefits (Watkiss *et al.*, 2019). For this reason, there has been a focus in the literature on decision making under uncertainty.

Additional complexity is added by the need to take a systems view (i.e. everything is interrelated and interdependent). No infrastructure network operates in isolation and a failure in one system can interact with others, and rapidly cascade into other sectors. Thus, system resilience to climate change goes beyond just the individual infrastructure networks. Indeed, interactions are not just limited to the infrastructure sector and can have far reaching consequences. As part of the 3<sup>rd</sup> Climate Change Risk Assessment, a project on Interacting Risks was commissioned to investigate this element (see Box 4.4).

### 4.1.3 Adaptation: Policy Considerations

The periodic CCRA is a requirement of the Climate Change Act 2008 and 2009 Climate Change (Scotland) Act. An additional key requirement in the Act was the production of climate change adaptation reports which can be requested by the Secretary of State. This process, known as *Adaptation Reporting Power* (ARP) in England, has been widely adopted across the infrastructure sector with a total of 91 assessments received during the first round of reporting. Although the process became voluntary in subsequent rounds, infrastructure related organisations / operators represent the vast majority of respondents (75/88) who have volunteered to report in the latest (third) round due in 2021. Although this is an excellent response rate, it is problematic for CCRA in two ways. Firstly, not all critical organisations are reporting and as such recommendations have since been made by the Climate Change Committee to reinstate compulsory reporting to ensure evidence is captured which is unable to be acquired easily by other ways. Secondly, the submission date for the third round of ARP is beyond the evidence capture phase of this CCRA and therefore is unavailable for inclusion and scrutiny. As such, there is a reliance on the second round of reporting, which demonstrated that whilst good consideration is being achieved in assessing risks and appropriate adaptation responses were underway, the reporting was too vague to provide any detailed assessment of progress (CCC, 2019b). Thus, steps 2 and 3 of the CCRA3 methodology which are focussed on adaptation consider reported progress on adaptation from the Climate Change Committee (Progress Reports), as well as input on policy developments from a range of industry representatives.

Policy continues to evolve in the infrastructure space, following on from the National Policy Statement (England & Wales) published in 2014, the Climate Change Adaptation Programme (Scotland) and the Northern Ireland Climate Change Adaptation plan. These have led to sector-level policy responses in the form of Sector Security & Resilience Plans (SSRPs), coordinated by the Cabinet Office Civil Contingencies Secretariat. Resilience of assets to relevant risks is detailed in the SSRPs, but as reported in CCRA2, there is no clear link between them and adaptation planning. Recent development in this area has been highlighted by the NIC (2020) which promotes a statutory requirement for regulators in the infrastructure sector to have resilience duties.

## 4.2. Risks to infrastructure networks (water, energy, transport, ICT) from cascading failures (I1)

Infrastructure operates as a system of systems. It means that vulnerabilities on one network can cause problems on others, and therefore be far reaching beyond the infrastructure sector. Given the wide-ranging nature of the linkages, a full understanding of the impacts of cascading failures is difficult to ascertain. However, the vulnerability of interconnected systems may be significantly underestimated (Mao and Li, 2018). This is increasingly evidenced, albeit anecdotally, by high-profile case studies, but the limitation of this approach means that it is difficult to understand, with confidence, the full magnitude of future risks in this area.

Case studies (such as the August 2019 power cuts) and literature support an assessment of current risk being high magnitude, with high confidence, with disruption in urban areas potentially impacting hundreds of thousands of people annually. Future magnitude is given as high with medium confidence for all four nations.

Whilst there are many examples of best practice adaptation within individual infrastructure sectors, the practice of focusing efforts in this way means opportunities are being missed to improve resilience across the sector more generally. The lack of a systematic national assessment of interdependency risk, the poor assessment of progress on adaptation in this area, and the low likelihood that sufficient non-governmental action will be undertaken indicates that this risk is not currently being managed, and that only partial plans are in place to do so. Because of the high projected magnitude for this risk and the view that current and announced adaptation will not fully manage the risk, it has been scored as more action needed across the whole of the UK.

### 4.2.1 Current and future level of risk (I1)

#### 4.2.1.1 Current risk (I1)

Note: it has not been possible to split the evidence by UK country for this risk.

##### 4.2.1.1.1 Current risk - UK-wide (I1)

Infrastructure networks do not operate in isolation. They can be interdependent because (i) their services are reliant on other networks for power, fuel supplies and ICT; or (ii) they are co-located and experience the same hazard; or (iii) they are managed or used by the same organisations or people (Dawson, 2015). As such, failures can cascade from one infrastructure network to another, often caused by multi-hazards, cascade hazards and compound hazards (AghaKouchak *et al.*, 2018).

Infrastructure systems featured heavily in CCRA3 research on Interacting Risks (WSP, 2020) (see Box 4.4), which provides an understanding of how risks can cascade across, and interact beyond, the infrastructure sector. Indeed, the majority of risks studied described interactions within the infrastructure sector, such as coastal flooding causing power infrastructure inundation, or power

supply interruption leading to impacts on travel and freight operations. However, there are also clear links to other sectors, such as water supply interruptions leading to health and welfare impacts (see Chapter 5, Health, Communities and the Built Environment: Kovats and Brisley, 2021). Overall, WSP (2020) identified 7 interactions with a high impact magnitude score for the baseline period, with 13 scored as medium and 7 as low impact. System interdependencies are mapped in the National Infrastructure Commission's Resilience Study, which details how national-level decisions (such as policies, incentives, markets and other factors) influence UK infrastructure Levels of Service (ARUP, 2020).

CCRA2 (Dawson *et al.*, 2016) specifically reported on interruptions to the supply of biomass to power stations following flooding of the Port of Immingham in December 2013. Critical power and IT services were lost, causing the cessation of operations for a number of days. In the same month, flooding of the M23 motorway and railway station hampered the ability of staff to travel to Gatwick airport. Flooding of substations during the event at Gatwick resulted in disruption to 13,000 airline travellers (McMillan, 2014). In addition to these previously reported examples, a further notable event was the loss of electrical power at a major exchange in Birmingham in 2011 which led to the loss of broadband connection to hundreds of thousands of customers in the UK (BBC, 2011).

More recently, power outages in England and Wales on the 9<sup>th</sup> of August 2019 demonstrate the potential for cascading infrastructure failure (Ofgem, 2020a). The event was triggered by a lightning strike on the Eaton Socon-Wymondley circuit between Cambridgeshire and Hertfordshire, causing a routine fault on the national electricity transmission system and the disconnection of a number of small generators connected to the local distribution network. Simultaneously, two larger generators (Hornsea 1 Limited and Little Barford) experienced technical issues and were unable to provide power. The combined power losses exceeded the back-up power generation capacity of the Electricity System Operator (ESO), triggering a power outage. A total of 892 megawatts (MW) of net demand was disconnected from local distribution networks. The electricity supply of over 1 million consumers was interrupted. The outage had significant knock-on impacts for the rail sector, with the Train Operating Company (TOC) Govia Thameslink Railway experiencing stranded trains, triggered by on-board automatic safety systems. This in turn caused knock-on delays across the rail network (Ofgem, 2020a). Hornsea 1 Limited and RWE Generation UK plc (operators of Little Barford) each agreed to make voluntary payments of £4.5m to the Energy Industry Voluntary Redress Scheme.

Storms, heavy rainfall and flooding are often precursors to cascade events (e.g. Storm Desmond (see above) and Hurricane Katrina, (Leavitt and Kiefer, 2006)). Indeed, the Environment Agency's long-term investment scenarios show that over 40% of transport and utilities infrastructure are in areas at current risk of flooding, either directly or due to dependence on other sectors (Environment Agency, 2019a). Further examples of the current magnitude of the impact of cascading failures include the flooding of a substation in Lancaster following rainfall associated with Storm Desmond in December 2015, leaving the city without power for more than 30 hours. This had consequences for transportation (no traffic lights, no lighting at the train station, refuelling issues), telecommunications (no mobile network, internet or digital radio), and water supply in some areas (Kemp, 2016; Ferranti *et al.*, 2017). In this example, the failure was caused by a combination of hazards; (i) eight weeks of wet weather had left the Lune catchment saturated, and water levels high, the two-day rainfall was (at the time) a rainfall record for Lancaster; and (ii) an incoming high

tide (Ferranti *et al.*, 2017). Although an extreme case, winters in the most recent decade in the UK (2009-2018) are now 12% wetter than 1961-1990, with the total rainfall from heavy rainfall events increasing by 17% (2008-2017) (Met Office, 2019a).

Since CCRA2, there have been several new academic approaches to studying interdependencies. For example, Pescaroli and Alexander (2018) have developed a framework to describe risk, classifying it as: compound, interconnected, interacting, and cascading. In addition, Murdock *et al.* (2018) presents a method for quantifying disruption caused by different failures to visualise information using interdependency circle diagrams. Crucially, recent international research has indicated that the vulnerability of interconnected systems may be underestimated. Mao and Li (2018) modelled the resilience lifecycle of an electric power system, a telecommunication system, and a water supply system and noted that excluding interdependencies gave a misleading impression of total resilience.

Much of the recent UK-based research on cascading risks from infrastructure interdependencies is focused on the potential impact of flooding hazards. Many of these studies use a simulation approach, for instance, Thacker *et al.* (2017a) simulate the interdependencies between the electricity network and the domestic flight network, demonstrating the potential for large disruptions resulting from the failure of electricity assets. Ranking the top 500 electricity transmission and sub-transmission assets in the UK, the simulation indicates that the most critical assets are capable of disrupting over 4 million customers. A similar picture is seen for potential disruptions to airport customers, with an increasing criticality at the higher tiers of the transmission hierarchy, but with individual assets at all levels capable of similarly high impacts (i.e. each impacting in excess of 190,000 customers). It must be noted that this is a simulation and has not been validated against real data. It is not clear whether the level of redundancy (i.e. the ability to manage disruptions through the network) during outages of key assets is reflective of the situation during observed events.

Thacker *et al.* (2017b) studied the spatial distribution of risk from cascading failures between infrastructure systems. By testing 200,000 failure scenarios, the study identifies that hotspots tend to be located at the periphery of urban areas where high concentrations of users will be impacted (hence demand) and critical infrastructures are concentrated.

Thacker *et al.* (2018) utilised an approach where data on critical infrastructure asset networks (including electricity generation, transmission and distribution, airports, water towers, wastewater treatment and telecom masts) are given synthetic connections based on distance and intersected with probabilistic hazard maps (in this case the National Flood Risk Assessment (NaFRA) flood likelihood map data) to calculate expected annual damages from flooding of electricity substations. Although simulated, the results show the potential for large-scale knock-on costs. The largest indirect sector impacts correspond to the business services and real estate sectors as well as the mining sector.

Pant *et al.* (2020) modelled a failure event initiated in the electricity network. The study estimated direct economic losses and total economic losses using an Input-Output (IO) model by assuming service disruptions lasted for 24 hours (with economic losses corresponding to losing demand from the equivalent of 24 hours of customers across sectors). Due to the forward and backward linkages

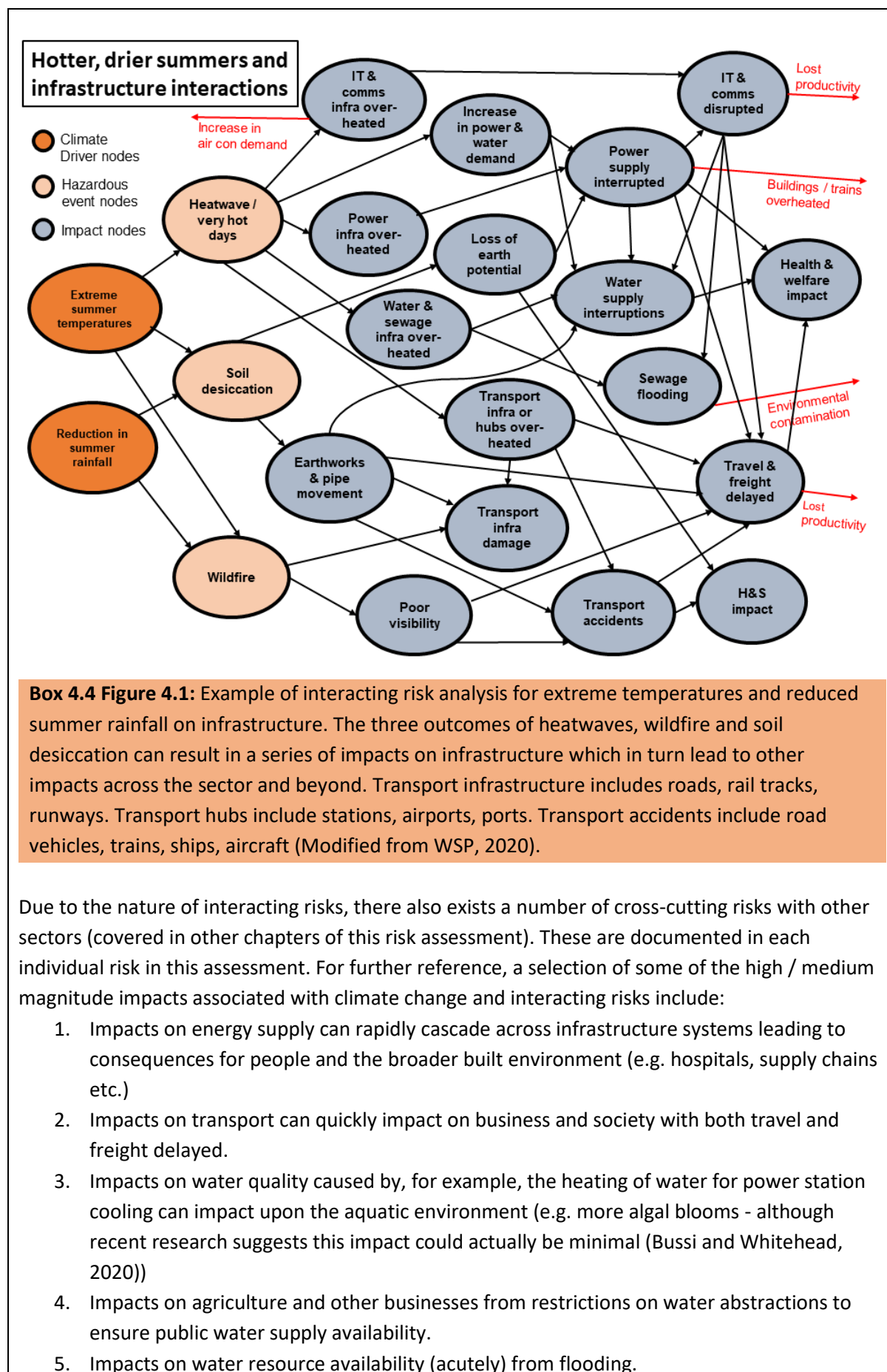


in the economic IO model, there are indirect economic losses to all sectors that use electricity, telecoms and railways outputs, and some of these losses feedback to these infrastructure sectors as well (Pant *et al.*, 2020).

Koks *et al.* (2019) used geospatial information on the location of electricity infrastructure assets and local industrial areas and employed a multiregional supply-use model of the UK economy to trace the impacts of floods of different return intervals across 37 subnational regions of the UK. The authors used the loss in labour productivity (temporary reduced employment) as the proxy for business disruption. The results show up to a 300% increase in total economic losses when power outages are included in the risk assessment, compared to analysis that just includes the economic impacts of business interruption due to flooded business premises (Koks *et al.*, 2019). The authors estimated that the total economic loss resulting from failure of five substations (worst case scenario) to be around £27 million per day.

#### **Box 4.4 Interacting risks and Infrastructure**

Interacting risks pose one of the biggest challenges when assessing climate risks more generally. Disruption on one infrastructure network can quickly cascade onto other infrastructure networks, but it is also important to recognise that infrastructure is a key enabler of the UK economy and underpins many key activities. The CCRA3 Interacting Risks project (WSP, 2020) demonstrated that the consequences of impacts due to climate changes on individual parts of the infrastructure network have far wider repercussions for the natural and built environment. Considering these wider effects, the magnitude of the impact far exceeds the effects on the infrastructure itself. There are numerous examples of this phenomenon. Interruption to power supplies is frequently highlighted as a key example of a source of cascade failure, but there are many others. For example, flooding (or other significant disruption) of transport networks can prevent key workers from operating other pieces of critical infrastructure. Fundamentally, access routes to key assets (e.g. nuclear power plants) may not be protected to the same level as the asset itself. Reliance on IT and communications infrastructure as an example of a current and increasing risk. Modelling of knock-on (downstream) nodes from a particular risk enables a qualitative assessment of further impact. Indeed, the interruption of power supplies is the single risk with the highest impact across the entire risk assessment and would be a root cause of large-scale impact across the sector. Disruption of IT and communication services is the second highest impact risk with significant downstream impacts. Other impacts were shown to be affected by a high number of risks further up a chain of interactions. The project found that risks emanating from other sectors caused delays to travel and freight more so than other impacts. As an example, Box 4.4 Figure 4.1 illustrates how these two risks can manifest as a direct result of extreme heat and a reduction in summer rainfall.



6. Impacts from displaced risks caused by flood management schemes (both coastal and fluvial)
7. Impacts on the marine environment from increased coastal erosion exposing old landfill sites.

Policy makers can use this information to better target adaptation efforts to improve the resilience against key risks which have the potential to cause the most upstream and downstream interacting impacts (e.g. multi-party agreements to allow the management of resilience risks by exploiting differences between sectors / locations). This has implications for the urgency in which measures are implemented.

#### 4.2.1.2. Future risk (I1)

Note: it has not been possible to split the evidence by UK country for this risk.

##### 4.2.1.2.1. Future risk – UK-wide (I1)

WSP (2020) projected the change in impact magnitude of infrastructure interactions for scenarios of global warming reaching approximately 2°C and 4°C in the late 21<sup>st</sup> Century (2070-2099) with large uncertainty<sup>1</sup>, scaled with macroeconomic growth (GDP and population growth projections) to account for future impacts being larger than today. This utilised the network maps showing principal interactions within and between the sectors (Box 4.4) with impacts being simulated based on knowledge of interactions between weather and the components in question. Projections for both the 2050s and the 2080s suggest that significant interactions in the infrastructure sector are more likely to occur and/or have greater impacts in the future, therefore with the current risk magnitude already high, the future risk magnitude can also be judged as high across the UK in scenarios of both 2°C and 4°C global warming at the end of the century (Table 4.2).

Impact ratings in the CCRA3 Interacting Risks magnitude framework are defined as follows for impacts on infrastructure:

**High** – Major annual damage and disruption or foregone opportunities (£hundreds of millions and/or hundreds of thousands of people affected)

**Medium** - Moderate annual damage and disruption or foregone opportunities (£tens of millions and/or tens of thousands of people affected)

**Low** - Minor annual damage and disruption or foregone opportunities (less than £10 million and/or thousands of people affected).

<sup>1</sup> UKCP18 probabilistic projections with RCP2.6 and RCP8.5 emissions, with 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentiles respectively reaching global warming of 1.1°C, 1.9°C and 2.8 °C (RCP2.6) and 3.0°C, 4.2°C and 5.8°C (RCP8.5) in 2070-2099. The RCP2.6 range approximately matches the lower CCRA3 scenario, and the RCP8.5 range includes the CCRA3 higher scenario but extends both slightly below and considerably above this (see Chapter 2: Watkiss and Betts, 2021).

**Table 4.2** Summary of the most significant risk pathways modelled in the CCRA3 Interacting Risks project (WSP, 2020), along with the impact ratings (based on annual average impact and likelihood) in 2020 and 2080.

Climate drivers	Hazardous events	Main impact cascades		2020	2080
Increase in summer temperatures and reduction in summer mean rainfall	Heatwaves and very hot days	Transport infrastructure overheating, or disruption to IT and communications services	Travel and freight delays	Low	Medium
			Transport infrastructure damage	Medium	Medium
Extreme winter rainfall events and increase in winter mean rainfall	River, surface and groundwater flooding	Power infrastructure flooded	Power supply disrupted	Low	Low
		Water, sewerage infrastructure flooded, reduced water quality or power supply disrupted	Water supply disrupted	Low	Medium
			Sewer flooding	Low	Medium
		Transport hubs or infrastructure flooded, or power supply disrupted	Travel and freight delays	Medium	High
		Damaging water flows, slope or embankment failure	Transport infrastructure damage	Medium	High

The most significant interactions are those which result in travel and freight delay or damage to transport infrastructure. The most significant cross-sectoral interaction highlighted was linked to natural environment interactions (e.g. flooding leading to reduced water quality in the natural environment leading to water supply disruptions). However, drought leading to low reservoir levels and water supply disruptions was also found to be significant in the 2050s and 2080s in the higher warming scenario by 2100 (changes in drought frequency are uncertain and were modelled on a

‘what-if’ basis in the project).

#### 4.2.1.3. Lock-in and thresholds (I1)

As highlighted in Box 2, the major cause of lock-in for this risk stems from high levels of infrastructure development planned for the near future (as per the National Infrastructure Plan). Infrastructure has a long lifetime and thus has an increased likelihood of facing future climate risks, while it could also be difficult or costly to retrofit adaptation later. In more specific terms, there is a concentration of lock-in risks because of an increasing reliance on electricity and ICT with all infrastructure sectors requiring power for some (if not all) of their assets. This situation is particularly acute in the transport sector due to the increasing electrification of transport systems and vehicles. The increasing dependence in utilities of telemetry/remote inspection means that the vulnerability to ICT failure is increasing very rapidly. Developments such as the likely introduction of autonomous transport technologies over the next 30-50 years will introduce new interdependencies and change the nature of cascading failure risks in the infrastructure system. Uptake of concepts such as digital twins, and the real-time management of assets management, will further increase reliance on power systems. CCRA2 noted there is insufficient information about the location of ICT and the criticality of its function. There are some modelling approaches that incorporate ICT systems, but these are not UK based.

Thresholds for cascade failure are difficult to define. When dealing with a system of systems, the network is effectively as strong as the weakest link. Although thresholds will exist for individual risks on individual assets, defining a clear threshold where a cascade failure will occur is an imprecise science given the range of compound hazards and interactions needing to be considered. This remains an important area for future research.

#### 4.2.1.4. Cross-cutting risks and inter-dependencies (I1)

Owing to its nature, this risk has interactions with many other risks within the infrastructure sector and beyond. As well as the information on interdependencies, WSP (2020) identified the impacts which have the greatest number of downstream connections (i.e. have the greatest potential for cascading failures throughout the infrastructure system and wider economy). In terms of infrastructure, power supply interruption has the highest number of connections (15, with 11 being in the infrastructure sector and 4 in the built environment), followed by IT and communications disruption (10, with 7 in the infrastructure sector and 3 in the built environment) and transport infrastructure/hub flooding (7, with 4 in the infrastructure sector and 3 in the built environment). Looking at impacts with large numbers of upstream connections (which can be affected from a number of different sources), those that are affected most by the infrastructure sector are travel and freight delays (13 connections with the infrastructure sector), water supply interruptions (9 connections), transport accidents, power supply interruptions, transport infrastructure damage and sewage flooding (all with 5 connections).

#### 4.2.1.5 Implications of Net Zero (I1)

At present, no studies have assessed the extent to which future socio-economic scenarios or

planned developments to achieve Net Zero in the UK will affect the exposure and vulnerability of infrastructure systems to climate hazards. However, power supply interruption, and transport infrastructure/hub flooding are both identified in the literature as highly connected impacts with high potential for cascading failures. Both of these systems feature heavily in the CCC Net Zero Technical Report (CCC, 2019b) and the CCC's 2020 advice on the Sixth Carbon Budget (CCC, 2020a) as key areas for meeting emissions targets, hence future exposure and vulnerability will potentially be influenced by forthcoming recommendations / policy in this area. It is therefore possible that the Net Zero target could concentrate system risks. As an example, electrification of cars (as well as household energy supply, see risk H6) will increase the potential impact of power shortages brought on by weather related events. The increase in future climate change and the growing level of potential interacting and cascading risks could make the Net Zero target more difficult to achieve, in that it is likely to involve additional costs (for climate smart design) and might require greater margins for management in the system.

#### 4.2.1.6 Inequalities (I1)

At present, no studies exist which specifically assess the observed inequality of risks to individuals/groups. The spatial hotspot analysis by Thacker *et al.* (2017a) demonstrates the importance of large urban areas of England and Wales for both demand for infrastructure services and their ability to accommodate these (especially in the periphery of urban areas). This analysis is based on simulation and also identifies important transport corridors between settlements. The CCRA3 interacting risks project (WSP, 2020) shows that of the 98 interactions (defined as a pair of connected hazardous event or impact nodes, excluding the climate driver nodes) taken into consideration in the infrastructure sector, 6 (2%) were defined as having coastal impacts only. For the remaining 92 interactions, the impacts are likely to be felt in multiple locations (i.e. both urban and rural areas, and the coastal zone). The study concludes that for the vast majority of interactions it is not possible to state that they are more important at one location over another. The consequences of this risk are high across England, Wales, Scotland and Northern Ireland.

#### 4.2.1.7 Magnitude scores (I1)

The case studies and literature support an assessment of current high magnitude of risk with high confidence, with disruption in urban areas potentially impacting hundreds of thousands of people annually. WSP (2020) supports a continuation of high magnitude risk in the future, given that the size of the impact from cascading effects increases over time.

Although the existing literature on the potential impact of climate change on cascading failures in the infrastructure sector is limited, the evidence for future risk to the individual components of the infrastructure system contained in this chapter (for example, risks to energy, risks to infrastructure from river, surface, groundwater and coastal flooding) supports a medium level of confidence for a continued high magnitude risk of cascading infrastructure failure for all nations of the UK for the 2050s and 2080s under pathways to 2°C and 4°C global warming at the end of the 21<sup>st</sup> Century.

**Table 4.3 Magnitude scores for risks to infrastructure networks (water, energy, transport, ICT) from cascading failures**

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Northern Ireland</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Scotland</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Wales</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)

#### 4.2.2 Extent to which current adaptation will manage the risk (I1)

##### 4.2.2.1. Effects of current adaptation policy and commitments on current and future risks (I1)

###### 4.2.2.1.1. UK-wide

The CCC (2019b) state there is no systematic national assessment of interdependency risk or a framework to improve resilience at the UK level, including addressing risks and opportunities from climate change. The general approach to manage cascade failure is by tackling individual risks on individual infrastructure networks. As a result, although the risks to individual components or systems are reduced, opportunities and efficiencies that could be gained by taking a whole-systems approach are often missed. As this work to build resilience is ongoing (at various levels), then the risk will be reduced somewhat by current adaptation efforts across specific sectors. The cumulative impact of these efforts on general cascade failures is unknown and as such expert judgement is required on the extent to which those efforts will manage the risk (as demonstrated in the CCRA3 Interacting Risks project).

A better understanding of cascade failures and improved efforts for data sharing could significantly reduce any adaptation shortfall. The OECD highlights the importance of specialist networking groups

such as the Infrastructure Operators Adaptation Forum in facilitating discussions between different infrastructure organisations and government, raising awareness, promoting collaboration and potentially increasing preparedness to reduce vulnerability (Vallejo and Mullan, 2017). In the UK, the 2004 Civil Contingencies Act provides a framework for cross-sectoral discussions on climate change adaptation within the broader context of disaster and crisis management. It created Local Resilience Forums (England and Wales, this is devolved for NI and Scotland), that bring together regional authorities and organisations, including category one responders, in order to create a risk profile for their region and produce localised regional plans and protocols to prepare for disaster management (Cabinet Office, 2013). Indeed, the Civil Contingencies Act places a duty on Category 1 and 2 responders to share information to enhance coordination, and the Green Book Guidance provides tools to identify and manage interdependencies that affect resilience in projects (HM Treasury, 2015), with supplementary information for policy makers and analysts (Defra, 2020a). There is ongoing work to share data with Local Resilience Forums across geographical and organisational boundaries via the Resilience Direct online platform. This is an online private 'network', which enables civil protection practitioners to share data during the preparation, response and recovery phases of an event or emergency. The platform is a secure site, and therefore requests to use evidence provided by other users have to be agreed by the user groups (Defra, 2018). In reality, the level of staffing, resources and materials varies between Local Resilience Forums (Quirk, 2019), potentially implying variability in local resilience (although this may be a rational response to lower vulnerability).

The devolved administrations are members of the Cabinet Office-led Infrastructure, Resilience and Security Working Group (IRSWG) and are working closely with the UK Government, each other and Local Resilience Forums on the existing risk to critical infrastructure. This includes work around the UK Sector Resilience Plans which set out risks to 13 sectors (including energy, transport and emergency services) and measures to improve resilience where necessary. It should be noted however that a review of LRF documents found little mention of managing cascading impacts.

The National Infrastructure Commission makes three recommendations to enable future resilient networks: firstly, that Government should introduce a statutory requirement by 2022 for Secretaries of State to publish five-yearly resilience standards, and an assessment of how infrastructure operators can deliver these standards; secondly, that by 2024, regulators should introduce a means to stress test infrastructure systems and decision-making to ensure that standards can be met; and thirdly, that infrastructure operators should develop and maintain strategies to ensure infrastructure services can continue to meet resilience standards in the long term (NIC, 2020)

While different aspects of infrastructure resilience are led at the UK level, the national adaptation programmes of each UK nation also include relevant information (with reserved matters included in the NAP2 document).

### 4.2.2.1.2 England

A CCC survey from 2014 (repeated in 2017) highlighted that Local Resilience Forums in England felt information was not being shared appropriately between them on infrastructure interdependencies (e.g. infrastructure operators and Category 1 and 2 responders). The second National Adaptation



Programme (NAP2) contains one action on dealing with cascading risks in infrastructure; 'help ensure local arrangements are in place to share data effectively on locally significant infrastructure sites with Local Resilience Forums'. The latest UK Government Response to the CCC's progress reports (HM Government, 2019a) pointed to the National Infrastructure Commission's report on resilience, the Adaptation Reporting Power, and the Infrastructure Operators Adaptation Forum as mechanisms to exchange information between providers but stated that further information was not available to the CCC as it is strictly confidential. The CCC is planning to update its survey of LRFs for its 2021 progress report to ascertain if progress has been made for these groups.

### 4.2.2.1.3 Northern Ireland

The latest Adaptation Programme for Northern Ireland (DAERA, 2019) contains an objective for transport and network services to be resilient to the impacts of flooding and extreme weather. The importance of interdependencies is mentioned throughout the document, though no specific actions are included to address cascading risks specifically.

### 4.2.2.1.4 Scotland

Scotland's most recent Climate Change Adaptation Programme (Scottish Government, 2019b) also mentions the importance of interdependencies between infrastructure sectors and includes a range of actions looking at supporting infrastructure systems to become more resilient in general. There are no specific actions that are included in response to this risk alone.

As an example of regional action, Glasgow has seen the creation of 'Climate Ready Clyde', bringing together a number of stakeholders including Local Authorities, SEPA, SGN, the NHS and Transport Scotland to develop Glasgow City Region's first Climate Adaptation Strategy. This strategy, which is currently in draft, outlines the processes and early interventions needed to manage climate risks, provides a strategic framework for adaptation, and sets out how the city will deepen and expand collaboration and collective impact between citizens and organisations (Climate Ready Clyde, 2020). Through the partnership, they have worked together on projects with wider infrastructure providers such as Scottish Water and Scottish Power Energy Networks to better understand regional interdependencies on infrastructure, producing new tools and assessments to deepen collective understanding. They have also produced a toolkit for assessing climate risk in built environment and infrastructure projects which includes a specific recommendation to consider cross-organisation risks and interdependencies.

### 4.2.2.1.5 Wales

In Wales, the Well-being of Future Generations (Wales) Act 2015 established Public Service Boards (PSBs) across the nation (Welsh Government, 2015). Each PSB must establish well-being plans, and in doing so, prepare well-being assessments which pay due regard to the latest UK Climate Change Risk Assessment. Alongside the well-being goals set out in the Act, the approach intends to support public services in Wales to achieve greater collaboration on cascading climate risks. Also, since the last CCRA, a National Infrastructure Commission for Wales was established. One of the key themes of the commissioner's 2019 report was resilience (National Infrastructure Commission for Wales,

2019). This recognition was reiterated in the 2020 report, where the commission has asked for evidence of risk management strategies (National Infrastructure Commission for Wales, 2020). This should prove an important tool in advising the Welsh Government on long term infrastructural needs.

The latest Welsh Climate Change Adaptation Programme (Welsh Government, 2019b) includes three specific actions aimed to address the cascading risks from climate change to infrastructure:

- Complete delivery of pilot exercise to improve emergency response to threats to infrastructure.
- Roll out new infrastructure emergency response processes across all Local Resilience Forums.
- Work with utility companies specifically to address the risk of a total failure of the UK's national electricity transmission network.

Prosperity for All: A Climate Conscious Wales (Welsh Government, 2019b) references a pilot being undertaken in the Dyfed-Powys region which brings together responder agencies and utility companies to strengthen preparedness around the various risks to infrastructure. Nevertheless, it is not clear to what extent climate risks are considered.

#### 4.2.2.2 Effects of non-government adaptation (I1)

Infrastructure operators are becoming increasingly aware of interdependencies and cascade failures and including them in their in-house research and longer-term strategic planning. A project funded by the International Union of Railways developed (with stakeholder consultation) a two-sided framework for use by any organisation to develop climate-change-ready transport infrastructure, regardless of their current level of knowledge or preparedness for climate change (Quinn *et al.*, 2018). The framework is composed of an adaptation strategy and an implementation plan, in order to embed climate change adaptation within organisational procedures so it becomes a normal function of business. However, there is little evidence to suggest that strategic actions to reduce exposure or vulnerability to climate change are happening (CCC, 2019b). Following Storm Desmond and Storm Eva (both December 2015), the electricity network companies have been reviewing and updating Engineering Technical Report (ETR) 138 – Resilience to Flooding of Grid and Primary Substations to consider enhancing the protection provided to primary substations supplying >10,000 ('key local infrastructure'), and identifying 'locally significant infrastructure (e.g. supply to rural communities) within the broader remit of considering interdependencies (Booth *et al.*, 2017).

#### 4.2.2.3. Is the risk being managed? What are the barriers preventing adaptation to the risk? (I1)

Despite the actions described above there is judged by the authors to be an adaptation shortfall for this risk given the lack of evidence on how far proposed actions listed above are reducing the current and future risk of cascading impacts. This assessment is similar to that in the most recent CCC Progress Report (2019) for England (and reserved matters at the UK level) which scored progress in this area as 1/10, with existing plans given a low assessment, stating that they do not clearly address the risks identified in CCRA2.

Fundamentally, this is an area where non-governmental action will not manage the risk in the absence of government intervention. Public bodies and private organisations that manage, operate and maintain infrastructure have to meet statutory requirements and performance standards for the services they provide, and climate change is one of the risk factors that they should account for in their decision making in order to fulfil their obligations. In the specific case of infrastructure networks, the presence of complex interdependencies coupled with uncertainty around climate change makes it challenging to fully understand and thus address the risks posed (information failures). Further, in dealing with cascading failures, which require some degree of system thinking, significant governance barriers exist, which affect not only the level of preparedness of the infrastructure network, but also the type of response to failures and disruptions. In fact, the interconnectivity between the infrastructure assets means that any poorly defined responsibilities, or lack of coordination between various operators, could undermine the ability to anticipate, react and recover from cascading failures. Government can play a key role in adopting a system-based approach to planning for resilience by providing the information to enable this, and providing infrastructure operators with a regulatory framework that supports adaptation at network level rather than at the level of individual assets.

The lack of a systematic national assessment of interdependency risk, the poor assessment of progress on adaptation in this area, and the low likelihood that sufficient non-governmental action will be undertaken indicates to the authors that this risk is not currently being managed, and that only partial plans are in place to do so. Although cascading failure and interdependencies are increasingly being acknowledged in policies, strategies and plans in place, these lack clear objectives following SMART principles (Specific, Measurable, Achievable, Realistic and Timebound, see National Audit Office, 2019) to reduce risk to a low magnitude, across the likely range of future climate scenarios. As there is no evidence base assessing the effects of future adaptation in managing the risk, this assessment must be given with low confidence.

#### 4.2.2.4 Adaptation Scores (I1)

<b>Table 4.4</b> Adaptation scores for risks to infrastructure networks (water, energy, transport, ICT) from cascading failures			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

#### 4.2.3 Benefits of further adaptation action in the next five years (I1)

##### 4.2.3.1 Additional adaptation that would address the adaptation shortfall (I1)

There are beneficial adaptation actions which could be enacted during the next five years. However, the benefits of these actions are often primarily aimed at a particular infrastructure system, and

hence also relate to other risks within this report. For instance, Thacker *et al.* (2018) demonstrate the benefits of bringing forward adaptation work in the protection of electricity substations. The study concentrates on the ETR 138 recommendations that major electricity assets be made resilient to a 1:1000-year flood. By simulating the potential costs involved in cascading impacts of flood-related substation failure it is found that (i) building a wall is cost beneficial for all substations; (ii) relocating the substation is not cost beneficial in most cases; and (iii) in approximately 50% of cases, raising the substation would be cost beneficial.

CCC (2017) argue that common standards of resilience (such as ISO 14091) would help with investment planning and help emergency planners better understand the potential for service disruption arising from assets in their area. ETR 138 'Resilience to Flooding' is given as a good example that has been adopted within the electricity transmission and distribution sector. It is stated that enhanced arrangements for information sharing on critical risks of interdependence are required to assist in creating the appropriate institutional conditions for adaptation.

#### 4.2.3.2. Indicative costs and benefits of additional adaptation (I1)

There is some evidence on the potential costs and benefits of adaptation for infrastructure investment (OECD, 2015) and in general positive benefit-to-cost ratios are reported for making infrastructure resilient (GCA, 2019). However, there is little evidence on the economic benefits for addressing cascading risks or moving to a systems-based approach. The studies that do exist tend to assess the additional benefits in considering indirect costs from adaptation (rather than just the avoided costs of damage to the infrastructure asset and operation itself), e.g. Thacker *et al.* (2018) for electricity substations, and Pant *et al.* (2020) for multiple networks. The consideration of indirect risks increases benefit streams and thus leads to higher economic benefits (and NPVs/BCR ratios). Evidence from other countries highlights that a systems-approach can also highlight the key vulnerability pinch points in networks, and thus help to direct adaptation, e.g. over-designing some key nodes or elements of the network.

#### 4.2.3.3. Overall urgency scores (I1)

**Table 4.5:** Urgency scores for risks to infrastructure networks (water, energy, transport, ICT) from cascading failures

Country	England	Northern Ireland	Scotland	Wales
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Medium	Medium	Medium

Due to the high projected magnitude for this risk and the lack of a systematic national assessment of interdependency risk, this risk has been scored as more action needed. Although the risk is recognised in the National Adaptation Programmes for each UK nation, there is presently limited evidenced progress on adaptation in this area, combined with little evidence to suggest that sufficient non-governmental action will be undertaken to keep the risk constant at today's level, or

reduce it in future. Policies, strategies and plans require clear SMART objectives to reduce risk to a low magnitude across the likely range of future climate scenarios. This score is given with medium confidence, noting the lack of specific evidence on benefits of future adaptation for cascading failure, but acknowledging a high level of agreement between experts.

#### 4.2.4 Looking ahead (I1)

In terms of considerations beyond CCRA3, including information that would be useful to inform CCRA4 and NAP4, it can be argued that the potentially beneficial measures identified above would be considered transformational, given the CCC's (2019b) low assessment of progress in this area. Much of the literature actually highlights that transformational adaptation requires a shift towards system thinking (e.g. Lonsdale *et al.*, 2015).

Practitioners have highlighted the need for more research into compound hazards, and that it would be useful to record and monitor impacts caused by cascading failures from weather and climate related disruptions (e.g. Storm Dennis). The CCC (2019b) similarly argue that a useful indicator would be to record and monitor impacts caused by cascading failures from weather and climate related disruptions.

### 4.3. Risks to infrastructure services from river and surface water flooding (I2)

Identified as a key risk with an adaptation shortfall in previous UK CCRA3s, river and surface flooding is a perennial risk to UK infrastructure, with each season adding new case studies and evidence to underpin the significant magnitude of the threat. The latest research indicates that all infrastructure continues to face an increased risk from surface water flooding with a continuation of the current level of adaptation ambition, and even in the most ambitious adaptation scenarios modelled for CCRA3. Projections of risk from river flooding are more mixed. Railway lines and stations continue to look increasingly exposed to fluvial flooding, but taking into account adaptation, the risk of fluvial flooding appears to now be reducing for energy and clean water infrastructure assets. The risk to landfill sites from both sources of flooding is low. The current magnitude of the risk is scored as high across the whole of the UK with high confidence. Future magnitude without additional adaptation is scored as high with medium confidence.

The evidence also highlights that despite progress, particularly through investment in flood defences, there exists an adaptation shortfall across the UK which will require further government intervention to overcome in the next five years. Taken together, this leads to an urgency score of more action needed.

### 4.3.1 Current and future level of risk (I2)

#### 4.3.1.1. Current risk (I2)

##### 4.3.1.1.1. UK wide

Since the previous CCRA, the UK has seen a number of high-profile flood events that have impacted infrastructure services. 2019 was a particularly significant year with winter flooding making the headlines in South Yorkshire, quickly followed by the impacts of Storm Ciara and Dennis in 2020. October 2018 saw significant flooding from Storm Callum impacting on infrastructure in Wales whereas 2016 and 2019 saw intense summer and autumn rainfall producing flash floods notably impacting several stations on the London Underground.

For infrastructure, Sayers *et al.* (2020) quantify the current number or length of assets at 'significant' risk (denoted as an annual probability exceedance of 1:75 or higher for river flooding and 1:30 or higher for surface water flooding). The infrastructure types assessed are rail line length and number of rail stations, clean water sites, sewage treatment works, power stations' electricity substations, and landfill sites. Flooding of health and emergency services infrastructure is covered under risk H12. Across the UK, hundreds of individual assets and hundreds of kilometres of train lines are exposed to significant levels of river and surface water flooding in each UK nation, though it has not been possible in the research to determine what percentage of the total numbers of assets is at risk. The figures exclude roads, ports, airports and digital infrastructure assets such as data centres and telephone exchanges. It should also be noted that the assessment does not take into account local measures implemented to reduce the risk of flooding such as placing assets on higher ground. The effects of flooding on road networks, in addition to damage to the roads themselves, are to service users. This is particularly significant when considering delays to emergency services. Pregnotato *et al.* (2016) assessed urban strategies for reducing the impacts of extreme weather including flooding on infrastructure networks. In this study, person delays experienced during transport on the road network in Newcastle were modelled to be 63 minutes and 119 minutes during a 1 in 10 and 1 in 200-year surface water flood respectively.

On the railways of Great Britain, Network Rail (2017a) reported that between 2006 and 2016 flooding caused an annual average of approximately £15 million in Schedule 8 compensation payments (paid to passenger and freight train operators for network disruption) between Network Rail and Train Operating Companies. It must be noted that the reported figures do not distinguish between river, surface and groundwater flooding and coastal flooding. Additionally, this figure does not include repair and remediation work following flood events. An analysis of different climate risks (flooding, landslide, extreme weather, high winds, precipitation change and sea level rise) on the UK rail network identified flooding as the greatest risk (Wang *et al.*, 2020).

In their review of drivers of urban flood risk, O'Donnell and Thorne (2020) point to the problems associated with ageing infrastructure, requiring replacement or upgrading at significant costs. It argued that rehabilitation of intra-urban assets is taking place at an insufficient pace to keep up with deterioration, representing an increasing driver of UK flood risk.

## 4.3.1.1.2. England

In England, the number/length of infrastructure assets at significant risk of surface water or river flooding is shown in Table 4.6 below (from Sayers *et al.*, 2020).

**Table 4.6.** Number or length of infrastructure assets currently exposed to ‘significant’ risk of surface water or river flooding in England

Infrastructure Asset	Exposure to surface water flooding (1:30 or greater)	Exposure to river flooding (1:75 or greater)
Water sites (no.)	43	19
Sewage treatment works (no.)	601	478
Power stations (no.)	170	53
Electricity substations (no)	463	143
Rail length (km)	1,691	444
Rail stations (no.)	450	44
Landfill sites	0	0

The Environment Agency (2018) assessed the costs of the widespread flooding in December 2015 and January 2016 following Storms Desmond, Eva and Frank. The storms were associated with record-breaking monthly rainfall for parts of the UK and led to extensive flooding in the North of England. The Environment Agency analysis produced high-level economic estimates of the costs following an approach utilised for estimates of the 2007 summer floods and the 2013 to 2014 winter floods. The best estimate for the impact on rail transport was £121 million at 2015 prices (with a range of £103 million to £129 million). This figure is based on Network Rail assessments of infrastructure damages and disruption payments. It must be noted that this figure includes capital and welfare damages associated with the collapse of a sea wall in the Dover Folkestone area which is related to Risk I3 (the report does not disaggregate these figures). It was also noted by Network Rail that it is sometimes difficult to distinguish between flood and storm damage.

Further evidence from the Environment Agency (2018) assessment of the 2015-16 storms gives a best estimate for the costs to road transport as £220 million (with a range of £165 million to £275 million) based on Department for Communities and Local Government and Highways Authority data. It must be noted that this figure includes capital and welfare damages associated with impacts not covered in this risk, such as the collapse of the Tadcaster Bridge (Risks I1 and I4) and a landslip on the A591 (Risk I5). The Environment Agency also assessed the costs to electricity infrastructure, utilising DECC estimates for operational and infrastructure costs of £11 million. This included 100,000 people who endured power cuts over three days following the flooding of a substation in Lancaster. It was deemed not possible to assess the economic impact on ICT associated with the flooding of a BT exchange in York and a Vodafone data centre in Leeds as data were not provided by the respective companies.

Booth *et al.*, (2017) assessed the impact of severe flooding of the River Lune during Storm Desmond in 2015. This caused defences to be overtopped at a 132 kV grid substation, and on Saturday 5<sup>th</sup> December the decision was taken to switch off supplies to 60,987 customers (which equates to a medium magnitude impact). At Kirkstall, in North Leeds, the defences were overtopped during

Storm Eva, in 2015) when the River Aire burst its banks - electricity supplies to over 27,000 customers in the nearby Leeds Central Business District were lost (medium magnitude).

Network Rail's most recent Weather Resilience and Climate Change Adaptation Plans for the English Routes of Anglia, London North East and East Midlands, North West and Central, South East, Wessex and Western report a combined annual average of £11.1 million of flood-related Schedule 8 payments (the compensation payments to passenger and freight train operators for network disruption) between 2006/07 and 2018/19. Note that this does not include costs of repair and remediation work, or Schedule 4 payments (compensation payments to passenger and freight train operators for Network Rail's possession of the network).

Pant *et al.* (2018) quantified infrastructure flood impacts in terms of disrupted customers linked directly to flood assets and customers disrupted indirectly due to network effects in the Thames catchment area. The likelihood of flooding to areas of land within the flood plain of 1 in 1000 year fluvial and tidal flooding scenario was considered. Wastewater treatment works were found to have the largest risks because large numbers of such assets are located directly in flood areas. Water storage assets were found to have relatively lower flooding risks being located away from flood zones or at elevation, as expected due to function. Likewise, telecom assets are also found to be located away from flood zones or at elevation. There are potentially high magnitude disruptions resulting from aggregated electricity failures.

#### 4.3.1.1.3. Northern Ireland

In Northern Ireland, the number/length of infrastructure assets at significant risk of surface water or river flooding is shown in Table 4.7 below (from Sayers *et al.*, 2020).

<b>Table 4.7. Number or length of infrastructure assets currently exposed to 'significant' risk of surface water or river flooding in Northern Ireland</b>		
Infrastructure Asset	Exposure to surface water flooding (1:30 or greater)	Exposure to river flooding (1:75 or greater)
Water sites (no.)	382	91
Sewage treatment works (no.)	0	0
Power stations (no.)	3	0
Electricity substations (no)	6	1
Rail length (km)	183	87
Rail stations (no.)	3	0
Landfill sites	0	0

The Department for Infrastructure NI has produced a technical assessment of future flood risks in 'The Northern Ireland Flood Risk Assessment' (DfI, 2018) it identifies areas of potential significant flood risk. Their mapping analysis highlights an additional 248 key service and transport infrastructure assets are at risk from climate change. The latest risk assessments and corresponding management plans are currently out for consultation (see 4.3.2).



## 4.3.1.1.4. Scotland

In Scotland, the number/length of infrastructure assets at significant risk of surface water or river flooding is shown in Table 4.8 below (from Sayers *et al.*, 2020).

<b>Table 4.8.</b> Number or length of infrastructure assets currently exposed to ‘significant’ risk of surface water or river flooding in Scotland		
<b>Infrastructure Asset</b>	<b>Exposure to surface water flooding (1:30 or greater)</b>	<b>Exposure to river flooding (1:75 or greater)</b>
Water sites (no.)	0	2
Sewage treatment works (no.)	20	63
Power stations (no.)	5	14
Electricity substations (no)	34	33
Rail length (km)	861	268
Rail stations (no.)	64	7
Landfill sites	5	1

Network Rail’s Scotland Route reported in their most recent Weather Resilience and Climate Change Adaptation Plan (2020a) that flooding accounted for 20.3% of delay minutes between 2006/07 and 2018/19. The annual cost of flooding through Schedule 8 payments averaged £1.32 million, with the highest year totalling £3.31 million. Note that this does not include costs of repair and remediation work, or Schedule 4 payments (compensation payments to passenger and freight train operators for Network Rail’s possession of the network).

## 4.3.1.1.5. Wales

In Wales, the number/length of infrastructure assets at significant risk of surface water or river flooding is shown in Table 4.9 below (from Sayers *et al.*, 2020).

<b>Table 4.9.</b> Number or length of infrastructure assets currently exposed to ‘significant’ risk of surface water or river flooding in Wales		
<b>Infrastructure Asset</b>	<b>Exposure to surface water flooding (1:30 or greater)</b>	<b>Exposure to river flooding (1:75 or greater)</b>
Water sites (no.)	62	35
Sewage treatment works (no.)	126	60
Power stations (no.)	0	0
Electricity substations (no)	72	57
Rail length (km)	809	345
Rail stations (no.)	79	30
Landfill sites	0	0

Network Rail’s Wales Route’s latest Weather Resilience and Climate Change Adaptation plan (2020b) reported that flooding was the most significant weather-related cause of delay between 2006/07 and 2018/19, costing a total of £5 million in Schedule 8 payments with an annual average cost of

£0.38 million and recording a maximum of £0.68million.

#### 4.3.1.2. Future risk (I2)

##### 4.3.1.2.1. UK-wide

Extensive modelling of future risk has been completed in Sayers *et al.* (2020). The CCRA3 Future Flooding project (Sayers *et al.*, 2020) provides bespoke flood risk projections for the whole of the UK, including information on how the outputs have been validated and similarities with other flood data used by the UK Government and devolved administrations. This work documents both the future exposure of infrastructure assets to climate change as well as the impact of adaptation measures with a range of results available via a future flood explorer tool. To assess this baseline level of risk, the 'reduced whole system' adaptation scenario has been used. The projections form the basis of the analysis for this risk, but other evidence sources are included where these have been identified.

##### 4.3.1.2.1.1 Surface Water Flooding

Sayers *et al.* (2020) project that all infrastructure assets across the four countries will face increased exposure to surface water risk in the absence of further adaptation action. In a scenario of 4°C global warming in 2100<sup>2</sup> ("4°C in 2100") and a scenario of low population growth, a potential doubling of risk is projected by the 2080s for power stations and electricity substations in England and railways in England, Wales and Northern Ireland. Only 5 landfill sites are currently deemed at risk from surface water flooding (all in Scotland) and this does not change in the future. Dozens of different scenarios are modelled and available through the Sayers results database (web link: [CCRA research - UK Climate Risk.](#))

Separate analysis from Dale *et al.* (2017) present results from the UKWIR rainfall intensity project. This assessed changes in 1 in 30-year storm rainfall quantities for use in sewer modelling and design. Large increases in storm rainfall were projected with a Convective Permitting Model and a scenario of 5.5°C global warming at 2100<sup>3</sup>. With no adaptation, estimated changes to storms show similar or higher changes to those currently used by the water industry - this could have significant impacts on the resilience of sewer networks in the future.

##### 4.3.1.2.1.2 River flooding

Sayers *et al.* (2020) reports more variable changes in flood risk to infrastructure assets from river flooding. Across the UK, in the reduced whole system scenario (which assumes adaptation to flood risk continues but implementation is in-line with a lower level of ambition, also described as 'no additional action') the level of risk decreases for clean water sites, power stations and electricity substations by between 0 and 70% by the 2080s in a scenario of +4°C in 2100 and low population.

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2 For the scenario of 4°C global warming in 2100, Sayers *et al.* (2020) used a subset of the UKCP18 probabilistic projections that reached 3.9°C to 4.1°C global warming in 2090-2100, relative to the 1850-1900 average.

3 Met Office regional climate model at 1.5km resolution (Kendon *et al.*, 2014) with boundary conditions from the HadGEM2-ES global climate model driven by the RCP8.5 concentration scenario, reaching global warming of approximately 5.5°C at 2100 (Betts *et al.*, 2015).

For sewage treatment works, rail lines and stations, there is generally either no change or an increase in risk of up to 80%. Only one landfill site is classed as being at risk from river flooding and this does not change in the future.

Climate change also impacts the standard of protection afforded by flood defences that help to protect sites from river flooding (Sayers *et al.*, 2020). In the absence of any further adaptation the reduction in the standard of protection provided by fluvial defences is mixed with some areas experiencing an effective increase in the standard of protection as peak flood flows reduce (reflecting the complex spatial pattern of future changes in peaks flows).

Bell *et al.* (2016) assessed the possible impacts of climate change on snow and peak river flows across Britain. The results indicate that in a scenario of +4°C at the end of the century<sup>4</sup>, the seasonality of peak river flows will be affected in some parts of the country by 2069-2099, with northerly regions tending to experience annual maxima earlier in the water year in future, with changes in southerly regions being less clear-cut.

Other evidence looking at the waste sector does suggest some risk. Some studies have looked at the risks to solid waste infrastructure indirectly through disruption to other infrastructure (e.g. failure of the electricity, gas or water supplies or disruption of transportation routes) (Ramsbottom *et al.*, 2012). Other sources of evidence suggest differently to Sayers *et al.* (2020) that flood risk will be the biggest threat to the sector, with increases in temperature also likely to require some changes to operations and management. Flooding of landfill sites usually results in an associated pollution event (Laner *et al.*, 2009; Neuhold and Nachtnabel, 2011).

Flood incidents can produce large amounts of waste within the flooded area; a minimum of 250 kg of additional waste per household is likely from a single flood (Watson and Powrie, 2015). However, the flooded area would need to include a significant (> 1,000,000) number of dwellings before this would have an impact on overall UK waste arisings.

#### 4.3.1.2.2. England

Sayers *et al.* (2020) project that in England, under a low population and no additional adaptation scenario, the risk of river flooding to sewage treatment works, railway line and railway stations increases at both the 2050s and 2080s. In a +4°C in 2100 scenario, there is a projected 32% increase in sewage works and length of rail at risk by the 2080s, with a 45% increase in railway stations at risk. The number of clean water sites, power stations and electricity substations are all projected to decrease in risk by at least 56% in the same period. For surface flooding, risk increases for all infrastructure assets at both the 2050s and 2080s. By the 2080s in a +4°C in 2100 scenario, the increase in risk ranges from 57% for railway stations to 114% for electricity substations.

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4 UKCP09 11-member perturbed-parameter ensemble of the HadRM3 regional climate model driven by the SRES A1B scenario.

#### 4.3.1.2.3. Northern Ireland

Railway lines are the only infrastructure type in Northern Ireland that Sayers *et al.* (2020) project to increase in risk from river flooding (under a low population and no additional adaptation ('reduced whole system' scenario). Risk increases by 50% by the 2080s in a +4°C in 2100 scenario. All other infrastructure types are projected to decrease in risk. For surface water flooding, increased risk is projected for freshwater sites, electricity substations, railway lines and railway stations. By the 2080s in the +4°C in 2100 scenario, this increase in risk ranges from 49% for freshwater sites to 137% for railway lines. The risk to power stations is projected to decrease under all scenarios.

#### 4.3.1.2.4. Scotland

In Scotland, Sayers *et al.* (2020) project that sewage treatment works, railway lines and railway stations will have an increased risk of river flooding. By the 2080s in a +4°C in 2100 scenario, this increase ranges from 5% for sewage treatment works to 70% for railway stations. All other infrastructure types are projected to decrease in risk. For surface water flooding all infrastructure types are projected to increase in risk, ranging between 27% for sewage treatment works and 64% for railway lines by the 2080s in a +4°C in 2100 scenario.

#### 4.3.1.2.5. Wales

Sewage treatment sites, railway lines and railway stations are projected to see an increase in risk of river flooding (Sayers *et al.*, 2020). By the 2080s in a +4°C in 2100 scenario, this increase in risk ranges between 16% for sewage treatment works and 79% for railway lines (all other infrastructure types are projected to decrease in risk). All infrastructure types are projected to be at a higher risk of surface water flooding, ranging from 26% for sewage treatment works to 110% for railway lines (by the 2080s in a +4°C in 2100 scenario).

In Wales, River Basin Management Plans (RBMPs) have been produced for Western Wales; Severn and Dee River and 11 catchment summaries focus on climate risks; soils, water, trees, biodiversity, water demand, and supply and character. Natural Resources Wales (2018) assessed that the following numbers of infrastructure sites in specific River Basin Districts are at increased risk from being affected by flooding with climate change: Dee, 445; Severn, 1658; Western Wales, 1658. The reports also assess the number of railway properties at risk from flooding with climate change: Dee, 3; Severn, 34; Western Wales, 11.

#### 4.3.1.3. Lock-in and thresholds (I2)

The major cause of lock-in is from 'business as usual' planning and infrastructure being added in the near future if resilience measures are not being added, the long operational life of assets and thus the likelihood of facing future climate risks, and because it could be difficult or costly to retrofit later. There is potential for lock-in if flood defences / stormwater systems are under-engineered to cope with projected changes in climate ('lack of action' lock-in). The latter is particularly difficult to fix in urban environments once installed. There are also implications for maladaptation with flood defences which effectively pass the flooding problem downstream.

Key thresholds exist as assets will be engineered to resist floods of a specified return period. For example, reservoir dams are engineered to withstand a 1:10,000-year flood (see case study), but other structures are only built to withstand 1:100-year or lower floods. However, given likely increases to flood risk, there is scope for an upward inflation in engineering codes. The Cabinet Office now recommends that any Critical National Infrastructure should be able to withstand a 1:200-year event, but there is a major difference whether this is a 1 in 200-year risk today, or one with future climate change (i.e. in the 2050s). This can have important cost implications, from the trade-off between higher standards of protection and costs today versus future resilience and has led to a greater focus on decision making under uncertainty.

#### 4.3.1.4. Cross-cutting risks and inter-dependencies (I2)

The CCRA3 Interacting Risk project (WSP, 2020) assessed the impact of river, surface and groundwater flooding on infrastructure to have a number of significant cascading impacts in the 2020s, 2050s and 2080s in scenarios of approximately 2°C and 4°C global warming in the late 21<sup>st</sup> Century<sup>5</sup>, both to infrastructure and other sectors. The direct impact of extreme rainfall events causes flooding of power infrastructure, transport infrastructure and hubs and water sewage infrastructure. WSP (2020) also identified indirect impacts of cascades from flooding causing slope and embankment failures leading to transport damage and subsequent travel delays, and cascades from power disruptions from flooding affecting transport, water supplies and building productivity.

Table 4.2 shows that the two most significant cascading risks are caused by flooding of transport infrastructure resulting in travel and freight delays, and slope and embankment failures which in turn lead to transport infrastructure damage. These were determined to have a 'high' score for impacts by 2080.

#### 4.3.1.5 Implications of Net Zero (I2)

Natural flood management is intertwined with Net Zero policy (see 4.4.2). Many hard protection measures have high embodied carbon, and thus there is more interest in nature-based solutions (ecosystem-based adaptation) as an alternative or as part of flood management portfolios. The Net Zero target is likely to increase the interest in these schemes. Flood risk can be reduced by slowing run-off implementing a range of natural flood risk management interventions and the use of sustainable urban drainage systems. Increased tree planting rates, primarily for carbon capture, in both rural and urban areas could have some impact on localised fluvial flooding. However, there is a limit to the effectiveness of natural flood management (Dadson *et al.*, 2017), and perversely the Net Zero target may make it more challenging to manage the risk, though the Environment Agency has developed a Carbon Planning Tool to assess carbon over the whole life of built assets. Also relevant is PAS 2080, a global standard for managing infrastructure carbon. At the same time, the increase in flood related risks to infrastructure services, might make Net Zero more difficult to achieve, in that it

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<sup>5</sup> UKCP18 probabilistic projections with RCP2.6 and RCP8.5 emissions, with 5<sup>th</sup> and 95<sup>th</sup> percentiles reaching global warming of 1.1°C to 2.8 °C (RCP2.6) and 3°C to 5.8°C (RCP8.5) in 2070-2099. The RCP2.6 range approximately matches the lower CCRA3 scenario, and the RCP8.5 range includes the CCRA3 higher scenario but extends both slightly below and considerably above this (see Chapter 2: Watkiss and Betts, 2021).

is likely to involve additional costs (for climate smart design) due to the greater margins or uplifts than currently required.

#### 4.3.1.6 Inequalities (I2)

Decisions on where investment is targeted towards flood defences remain a challenge. There is a need to identify critical single points of failure in networks which have the biggest impacts for the largest groups of people. However, protecting these may move the problem elsewhere due to the available funding reallocated to other areas which may have lower populations but a higher proportion of socially vulnerable groups. The type of spatial location will also determine the extent to which disruption can be overcome, with potential inequalities for populations in rural locations with options for different service providers. For instance, cities may have multiple broadband providers, whereas this may not be the case in the country.

#### 4.3.1.7 Magnitude scores (I2)

<b>Table 4.10</b> Magnitude scores for risks to infrastructure services from river and surface water flooding					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Northern Ireland</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Scotland</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Wales</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)

Evidence on the impact of flooding events on infrastructure in the UK supports a current high magnitude with high confidence. Evidence from the Environment Agency (2018) on the 2015-2016 storms in England demonstrates costs to the infrastructure sector in the £100s of millions with hundreds of thousands of people affected. Best estimate figures include £121 million to rail, £220 million costs to roads and £11 million to electricity (although damages associated with other risks in

this assessment, such as landslips, should be noted). Annual figures on impact across the infrastructure sector are partial, but also indicate that magnitude is high on an annualised basis.

Network Rail reported an annual average of approximately £15 million in compensation payments to passengers related with flooding on their network, which does not include remediation and repair work. The stock of assets exposed to current hazard identified by Sayers *et al.*, (2020) and the vulnerability demonstrated in cost assessments of previous events supports high magnitude with high confidence across the four nations of the UK for infrastructure as a whole. It must be noted that the evidence (particularly annualised data) is uneven in quality and availability between infrastructure types.

Projections by Sayers *et al.* (2020) using UKCP18 indicate that all four UK countries will face increased exposure to surface water risk for all infrastructure types in the absence of further adaptation, with some scenarios seeing a potential doubling of risk by the 2080s in a +4°C in 2100 scenario and a low population growth scenario. Projections for risk from river flooding are more mixed, but sewage treatment works, rail lines and stations see either a maintained or increased risk. It is the judgement of the authors that without further adaptation, the risk will remain high for all four countries under all assessed climate scenarios.

### 4.3.2 The extent to which current adaptation will manage the risk (I2)

#### 4.3.2.1. Effects of current adaptation policy and commitments on current and future risks (Risk I2)

##### 4.3.2.1.1 UK-wide

CCRA2 determined with medium confidence that there is likely to be a significant adaptation shortfall in the future for this risk across the UK. The rationale centred around the fact that although resilience initiatives such as the Cabinet Office Critical Infrastructure Resilience programme and Sector Security and Resilience Plans have been established in the late 2000s, there had, at that point, been no published account of achievements in improving resilience of infrastructure systems to flood risk. It was stated that few sectors systematically report on the resilience of their assets and disruption caused by flooding (particularly non-regulated sectors such as ports and digital networks, as well as local infrastructure).

A UK Coordination Group (comprising representatives of the 4 nations – Environment Agency, SEPA, NRW, DfI NI) share information about allowances for Climate Change in Flood Risk Management and for Development Planning. The Group is reviewing the latest UKCP18 information and developing adaptive policies for their respective jurisdictions (primarily allowances for increased sea level rise, river flows and rainfall intensities along with associated planning advice). The implementation of the resulting guidance on allowances will provide a sound basis for ongoing adaptation activities to manage flood risk across the UK.

Sayers *et al.* (2020) argue that flood risk is best managed through a portfolio of measures implemented through a continuous process of adjustment. This portfolio approach has been adopted in recent policy such as the Scottish Government's 'Delivering Sustainable Flood Risk

Management’ (2019c), the Well-being of Future Generations Act in Wales (2015), the 25 Year Environment Plan (HM Government, 2018) and Defra’s second National Adaptation Programme 2018-2023 (Defra, 2018). Recent flood policy updates (Defra’s Policy Statement (2020b), the Environment Agency’s National Flood and Coastal Erosion Risk Management Strategy (2020a), and the Welsh Government’s National FCERM Strategy for Wales (2020a)) are calling for higher levels of ambition on managing flood risk, which could, if implemented, move adaptation towards the ‘enhanced whole system’ scenario modelled in Sayers *et al.* (2020) as a maximum reasonable adaptation scenario. The flood and coastal erosion risk management policy statement published in July 2020 (HM Government, 2020a) notes the importance of securing multiple benefits and how local plans will link with wider plans for an area, such as water resource plans, as well as with local nature recovery strategies. The National Strategy for Flood and Coastal Erosion Risk Management in Wales also takes a systemic approach, strengthening policies on communication, catchment approaches, collaborative working and forward planning. It complements new legislation to not only reduce present risk but also prevent issues for future generations through informed, place-based decisions. The recent improvements to asset data and mapping, alongside new guidance on natural flood management and investment, aim to make a strategic approach possible and more widely understood by the public and those responsible for delivery.

Sayers *et al.* (2020) point to Natural Flood Management (NFM) (also known as Working with Natural Processes (WwNP)), as a supporting measure in flood risk management (capable of delivering multiple outcomes). They include measures such as upland storage, the management of run-off from agriculture, floodplain/river restoration and tree planting, and are promoted in guidance by the Environment Agency and DfI Rivers, the EU Floods Directive 2007, Scotland’s Flood Risk Management Act, the Welsh Government’s FCERM Strategy (which aligns with the National Resources Policy) and England’s 25 Year Environment Plan. Planning is assisted by NFM opportunity maps which have been produced for England and Wales, Scotland, and Northern Ireland. In Wales, implementation of Schedule 3 of the FWMA commenced in January 2019, with all new development at or above 100 square metres needing to obtain approval for their drainage measures (using SUDs hierarchy) before work can commence on site. Similarly, Blue-Green infrastructure and Blue-Green Cities utilising ‘Green Infrastructure’ or SuDS (Sustainable Drainage Systems), are also promoted in guidance, e.g. the Core Strategy and Urban Core Plan for Gateshead and Newcastle upon Tyne 2010-2030, the Newcastle Local Flood Risk Management Strategy (Newcastle City Council, 2016), and the Ebbsfleet Implementation Framework (Ebbsfleet Development Framework, 2017).

#### 4.3.2.1.2 England

Under the Current Levels of Adaptation (CLA) scenario, which assumes a present day level of ambition in flood policy to be continued into the future, Sayers *et al.* (2020) project that risk of river flooding still increases compared to the present day for all those infrastructure types identified as increasing in risk under the Reduced Whole System (RWS) scenario, though the increase is less than in the baseline scenario. These are sewage treatment works, railway lines and railway stations. This is also the case for surface flooding, with freshwater sites, sewage treatment works, power stations, electricity substations, railway lines and railway stations all increasing in risk compared to the present day (with modest decreases compared to the projections for RWS).



The Environment Agency provides guidance on adaptation schemes and strategies for infrastructure from river flooding for England (Environment Agency, 2020a; Reynard and Kay, 2017), which includes projections of the anticipated change for peak river flows (referred to as 'climate change allowances'). They vary by river basin district, and with the period of time into the future. This information provides asset owners with a basis upon which to develop their own flood risk assessments as well as to underpin assessments for new developments.

O'Donnell *et al* (2017) argue that the implementation of innovative urban flood risk management approaches and infrastructure is hampered by socio-political, biophysical and governance barriers, particularly the failure in England to enact Schedule 3 of the 2010 Flood and Water Management Act. This would mandate surface water drainage for new developments to comply with mandatory National Standards for SuDS. The authors conclude that the intensity of the urbanisation driver of flood risk has not changed. O'Donnell and Thorne (2020) argue that strong business cases, supported by monetised evidence of benefits, and collaborative, inter-agency working could advance implementation of Blue-Green infrastructure within current flood risk management legislation.

Conversely, a 2018 government review by the Ministry of Housing, Communities and Local Government on the application and effectiveness of planning policy for sustainable urban drainage (SuDS) found that the majority (80%) of adopted local plans (and just over 90% of emerging plans) contained policies that clearly reflect the requirements of the National Planning Policy Framework (NPPF). Although the requirement in the NPPF refers only to major developments (see Risk H3).

#### 4.3.2.1.3 Northern Ireland

As with England, all infrastructure projected to be at increased risk of river and surface water flooding under the RWS scenario in Sayers *et al.* (2020) is also projected to increase in risk under the CLA (Current Levels of Adaptation) scenario. For river flooding, only railway lines are projected to increase in risk from river flooding, whereas freshwater sites, electricity substations and railway stations (as well as railway lines) are projected to see an increase in risk from surface water flooding. The draft Flood Risk Management Plan (FRMP) for the period 2021 – 2027, aimed at managing and mitigating the risk of flooding in Northern Ireland, has been published for a six-month public consultation (December 2020 until June 2021); the FRMP will be finalised by December 2021. The Plan focuses on 12 Areas of Potential Significant Flood Risk (APSFR) which were previously identified in the 2018 NI Flood Risk Assessment (DfI 2018). In addition, 9 'Transitional Areas of Potential Significant Flood Risk' (TAPSFR), identified as APSFR in the 2011 PFRA, have been determined to ensure continuity between FRMPs and facilitate implementation of any outstanding commitments arising from delivery of objectives and measures within the 2015–2021 FRMPs. For Northern Ireland, 'medium probability' scenarios have been considered in assessing the impacts of Climate Change on flood risk for the 2080s epoch.

DfI sits on the UK Coordination Group (chaired by DEFRA) as competent authority for the implementation of the EU Floods Directive in Northern Ireland. As a requirement of the EU Floods Directive, DfI Water and Drainage Policy Division along with its stakeholders is currently preparing the 2<sup>nd</sup> cycle of Flood Risk Management Plans for Northern Ireland (mentioned above). Climate change is an aspect which must be considered in this planning cycle. The new Flood Risk

Management Plan will highlight the flood hazards and risks in the Areas of Potential Significant Flood Risk in Northern Ireland from rivers, the sea and surface water. The plan identifies the objectives and measures that will be undertaken to manage the risk of flooding and sets out how the relevant authorities will work together with communities to manage flood risks. Currently NI allowances for flood risk management and development planning (primarily allowances for increased sea level rise, river flows and rainfall intensities along with associated planning advice) are based on UKCP09 information but the desire for NI is to move to new allowances based on UKCP18 information, which will be supported through the UK Coordination Group.

NI Water (2020) recently published 'Our Strategy 2021-2046' which recognises the climate emergency as one of six strategic risks for the next 25 years. Most of the urban areas in Northern Ireland are served by combined sewers that carry both sewerage and surface water which is inefficient and results in pollution and flood. NI Water plans to gradually transform the sewerage network by taking every economically viable opportunity to disconnect surface areas from existing combined sewers, for example when laying a new storm sewer to service a new development. In many locations this will help free up capacity in combined sewers for new connections without having to lay new or combined sewers. NI Water will actively promote the use of green infrastructure such as sustainable drainage systems (SuDS) in new developments by providing clear guidance to developers. NI Water will retrofit SuDS where it helps to reduce the risk of flooding and facilitates storm separation.

#### 4.3.2.1.4 Scotland

Sayers *et al.* (2020) project that all infrastructure types that are projected to increase in risk from flooding under the RWS scenario are also projected to increase in risk under the CLA scenario, though to a lesser degree. For river flooding these are sewage treatment works, railway lines and railway stations. For surface water flooding power stations and electricity substations, sewage treatment works, railway lines and railway stations are projected to increase in risk compared to the present day.

The SCCAP2 (Scottish Government, 2019b) describes current and planned flood risk management actions in Scotland. Scotland's Flood Risk Management Act (2009) encourages a sustainable catchment-based approach. This incorporates coordination between 'responsible authorities' (stakeholders) and the creation of plans for local districts and potentially vulnerable areas, and SEPA's subsequent Flood Risk Management Strategies, covering 2015-2021. These plans include the actions to be taken over a six-year flood risk management cycle (2016-2022). These are aided through SEPA flood maps and the Mapping Flood Disadvantage Tool, which are used in identifying priority areas for emergency services and to communicate flood risk issues to local communities. SEPA is creating a new Flooding Strategy "One Planet Prosperity" which aims to embed adaptation as a key principle to ensure flood risk management plans and actions tackle future flood risk through support to individual and community resilience to flooding.

A working group on surface water management has been established under the Scottish Advisory and Implementation Forum for Flooding (SAIFF). It includes representatives of Scottish Water, local authorities, SEPA and the Scottish Government. Surface water management planning guidance was

published in 2018, to support responsible authorities in preparation of Surface Water Management Plans (SWMPs) to help with the management of surface water flooding. The Flood Risk Management Strategies and Plans include actions in the first six-year cycle to prepare Surface Water Management Plans.

The Flood Risk Management (Scotland) Act 2009 places a duty on local authorities to map SuDS in their area, although there is no statutory timescale for doing this. Any SuDS (or other actions to reduce the risk of surface water flooding) that are retrofitted for the purposes of flood risk management will be in the Flood Risk Management Strategies and Local Flood Risk Management Plans. If SuDS are retrofitted for other purposes (e.g. water quality) then they may not be in the Flood Risk Management Plans. In Scotland, there is also a requirement for SuDS for all developments other than single dwellings. Surface water drainage in Scotland falls under Scottish Water and the road authority who are responsible for sewers and roads respectively.

#### 4.3.2.1.5 Wales

Sayers *et al.* (2020) project that all infrastructure types that are projected to increase in risk from flooding under the RWS scenario are also projected to increase in risk under the CLA scenario, though to a lesser degree. For river flooding these are sewage treatment works, railway lines and railway stations. For surface water flooding electricity substations, sewage treatment works, freshwater sites, railway lines and railway stations are projected to increase in risk compared to the present day.

In Wales, the Future Wales: National Plan 2040 (Welsh Government, 2021a) along with the Flood and Coastal Erosion Risk Management Strategy (Welsh Government, 2020a) provides a distinct approach from the rest of the UK, driven through the Environment Act (Wales) 2016 and Natural Resources Policy. These place a major emphasis on the role of resilient ecological networks, green infrastructure and nature-based flood risk management in managing climate risks to infrastructure over the long term.

The National Strategy for Flood and Coastal Erosion Management in Wales sets the overall policy framework for Local Flood Management Strategies delivered through Natural Resources Wales and local authorities. For climate change, one key point states that risk management authorities (RMAs) should use UKCP figures in their local and regional responses. In addition, the National Strategy commits to respond to the increasing risk from climate change by building a stronger pipeline of FCERM projects and updating long-term investment requirements using the latest climate change risk data. A national Flood & Coastal Erosion Committee was established in 2019 alongside the Wales Coastal Monitoring Centre. The Welsh Government's adaptation plan, *Prosperity for All: A Climate Conscious Wales* (Welsh Government, 2019b), sets out further measures to adapt infrastructure to these risks. The government has committed to a review of transport case studies to share best practice in transport adaptation and research is planned to review risks to bridges and pipelines at risk from river flooding and bridge scour in order to target intervention (see risk I5).

River Basement Management Plans have been established across Wales and recognise the risks posed from climate change and increased likelihood of flooding. Commitments are made throughout

with regards to various infrastructure, such as sewerage systems, drainage, and the use of sustainable blue and green infrastructure where possible (including SuDS).

#### 4.3.2.2 Effects of non-government adaptation (I2)

The electricity transmission and distribution network industry was deemed to have made the most progress in systematically assessing flood risk (CCC, 2019b). It has developed cross-industry technical standards for managing current and future flood risk and applies a consistent approach in identifying critical assets at high levels of risk. This is reflected in the future flood risk project (Sayers *et al.*, 2020). This information is used to make business cases to the relevant regulator to fund cost-beneficial resilience measures through the price control process. Substations serving one million customers were assessed to have benefitted from flood protection measures from investment planned between 2011 and 2023, with £172 million being allocated. The standard (ETR 138) may be reviewed in light of the National Flood Resilience Review and improved climate modelling.

Planned actions by electricity supply, transmission and distribution companies are expected to see over 90% of substations deemed at risk of flooding become resilient to 1 in 1000-year flood events by 2021. This is in line with standard ETR 138, which applies this requirement to primary substations with over 10,000 connections. This standard includes an assessment of the risks from flooding to all new and existing sites. It is not clear what actions are being taken for non-primary substations. It was reported that plans to manage risks to nuclear infrastructure include consideration of all relevant hazards. However, although the Cabinet Office set a benchmark that essential services provided by Critical National Infrastructure (CNI) should not be disrupted by a flood event with an annual likelihood of 1 in 200 (0.5% annual probability), it was not explicitly clear how this benchmark was being interpreted by sector, or the extent to which this standard was now in place. This makes it difficult to assess how risk is being managed autonomously. It was stated that more consideration of the resilience of systems as well as individual assets needs to be made.

The rail network benefits from specific actions targeted on flood risk, as noted for example in the Network Rail NW&C Region Weather Resilience and Climate Change Adaptation (WRCCA) Plan (Network Rail, 2020b) and more broadly in the Network Rail Weather Resilience and Climate Change Adaptation Strategy (Network Rail, 2017a). For example, In Scotland, flooding has been allocated over £13 million in funding between 2019-2024 to alleviate or reduce risk at 32 known flooding sites (Climate Ready Scotland action references NRCRS3 and NRCRS5). Network Rail Regions are tasked with providing updates on implementation of their WRCCA Plans to ORR and the central to the WRCCA Team twice a year, with the WRCCA Working Group reviewing progress and identifying improvements.

In telecommunications, the CCC (2019a) report there has been a push by the industry to improve resilience following the National Flood Resilience Review (NFRR). Ofcom published revised security guidance in 2017, including requirements to meet NFRR obligations and to ensure all sites (not just those in scope of NFRR) are protected from flooding. The NFRR accounts for climate change, however the review is limited to the next 10 years and it is not known if sanctions are applied by Ofcom for non-compliance.

With respect to waste, much of the existing infrastructure is likely to have been upgraded or

replaced by 2050. Any new waste facility whether entirely new or constructed for replacement or upgrade and the development of new waste facilities would be required to follow the latest planning rules in the National Planning Policy Framework (MHCLG, 2019). This explicitly requires that developments in flood risk areas should be avoided and if unavoidable, “the development should be made safe from flooding for its lifetime”. Any additional requirements to increase resilience should be included in the permitting process (the Environment Agency permit allows the operation of waste facilities) allowing the mitigation of some of the effects of climate change.

Landfill sites have a much longer lifetime than other waste facilities and it is likely that most modern landfills (those with engineered liners) will retain the ability to pollute the surrounding environment for perhaps as long as a millennium (Bebb and Kersey, 2003; Hall *et al.*, 2007). This pollution potential could be reduced by changing landfill management practices to accelerate degradation or by removing the waste through landfill mining (Watson and Powrie, 2015). This would suggest that of all solid waste management infrastructure, landfill sites are the most vulnerable to long term climate change.

#### 4.3.2.3. Is the risk being managed? What are the barriers preventing adaptation to the risk? (I2)

For risks which are currently medium or high magnitude today, the CCRA3 framework considers risk to be managed if the drivers of vulnerability and exposure are being well managed (today and in the future), and recent climate trends are well accounted for in the policies. The score of ‘partially’ managed reflects the evidence indicating that progress on flood defences has been made, though not enough to fully manage the risk. Evidence of SMART (Specific, Measurable, Achievable, Realistic and Timebound) objectives such as ETR 138 is available, but not widespread. In the CLA scenario in the Sayers *et al.* (2020) analysis, which represents planned and announced adaptation, future exposure is reduced compared with the RWS scenario (representing a scenario with no additional adaptation), but does not reduce exposure compared with the present day. It is noted that recent flood policy updates are calling for higher levels of ambition on managing flood risk, which could if implemented move adaptation towards the ‘enhanced whole system’ scenario modelled in Sayers *et al.* (2020) as a maximum reasonable adaptation scenario. It must be noted that even in this scenario, exposure would not be brought back to current levels for infrastructure projected to see an increase in exposure under the less ambitious RWS and CLA scenarios.

#### 4.3.2.4 Adaptation Scores (I2)

**Table 4.11** Adaptation scores for risks to infrastructure services from river and surface water flooding

Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)

### 4.3.3 Benefits of further adaptation action in the next five years (I2)

#### 4.3.3.1. Additional planned adaptation that would address the adaptation shortfall (I2)

As recommended in CCRA2 (Dawson *et al.*, 2016), there remains a need for the development of consistent indicators of network resilience to flood risk across all critical national infrastructure sectors and networks. Such indicators would help to create the institutional conditions for adaptation and would allow for improvements to be measured over time. This could build on improvement in local hazard information, such as the Cabinet Office's Resilience Direct platform which provides street-level surface water flood forecasts to authorities and category 1 and 2 responders.

In response to modelled impacts on emergency services due to observed surface and fluvial flooding in York, Coles *et al.* 2017 argued that an appropriate adaptation strategy should identify areas on the road network that are most vulnerable to flooding, as well as parts of the road network that are crucial for emergency services, e.g. access to hospitals. Green *et al.* (2017) recommended that the ambulance service should ensure that they are situated at strategic stand-by points during flood conditions to minimise the impact of a blocked road network on delaying emergency response to vulnerable locations.

For urban road transport, Pregolato *et al.* (2016) suggest both green infrastructure and conventional engineering measures to improve resilience. Spatial distribution of green roofs reduced person delays during a 1 in 10-year flood by 26%, compared with 12% from hard engineering measures for a single junction (both are compared with the effects of a 1 in 10-year flood with no adaptation), which highlights the potential benefits of blue-green infrastructure for urban flood resilience. The economic feasibility of this measure has not been assessed.

As covered in Risk I1, Thacker *et al.* (2018) demonstrate the benefits of bringing forward adaptation work in the protection of electricity substations. It is estimated that if National Grid brought forward the entirety of planned works scheduled for 2022, this would result in additional savings of £133,260,000 in avoided expected annual losses (although this would be constrained by planning and time scale). It must be noted that this research is based on simulation work.

#### 4.3.3.2. Indicative costs and benefits of additional adaptation (I2)

There is evidence on the potential costs and benefits of further adaptation. Much of this indicates high economic benefits from investing in flood adaptation for infrastructure (OECD, 2015: GCA, 2019). However, some care should be taken in interpreting this evidence, as much is based on 'predict and optimise' studies (where future risk levels are known), rather than an analysis taking account of uncertainty (and thus the potential for under or over investment).

The effects of different adaptation strategies on the annual expected damages from river flooding in the UK can be estimated from a recent EU+UK-wide regional climate change impact assessment (Dottori *et al.*, 2020), which used a regional-scale hydrological model with country-specific flood depth-damage functions to simulate economic damages under different global warming and

adaptation scenarios. Without adaptation, annual expected damages increase from 0.03% of UK GDP nowadays, to 0.04 and 0.06% of GDP with 2°C and 3°C global warming respectively (assuming the population and economy of 2100). However, the impacts are significantly reduced with adaptation. With 3°C global warming by 2100, the reduction in expected annual damage compared with no adaptation, in 2100, is 87% for raising of dykes, 94% for retention areas, 39% for relocation of built-up areas and 50% for building damage reduction measures.

More generally, there are a range of low-regret measures that have been identified in this area (Vallejo and Mullan, 2017; Watkiss *et al.*, 2019), which include:

- Supporting decision-making by providing tools and information,
- Screening climate risks (climate risk management) in public investments,
- Screening climate risks (climate risk management) in private sector investments,
- Enabling infrastructure resilience through policy and regulation,
- Encouraging the disclosure of climate risks/uptake in commercial finance,
- Supporting innovative risk spreading (insurance).

There are also estimates of the economic benefits and costs of some green infrastructure (McVittie *et al.*, 2017), though these are often site-specific. It is highlighted that there are important governance challenges, as well as opportunity and transaction costs associated with green infrastructure (Watkiss *et al.*, 2019). The benefit to cost ratios of SuDS have been studied (e.g., Ossa-Moreno *et al.*, 2017), and guidance exists for estimation (Benefit of SuDS Tool (BeST) (UKCIRIA)), although the financial case alone does not appear to incentivise adaptation.

#### 4.3.3.3. Overall urgency scores (I2)

Because of the high projected magnitude for this risk and the view that current and announced adaptation will not fully manage the risk, it has been scored as more action needed across the whole of the UK. Low-regret actions identified include supporting decision-making by providing tools and information and screening climate risks (climate risk management) in public and private sector investments.

**Table 4.12** Urgency scores for risks to infrastructure services from river and surface water flooding

Country	England	Northern Ireland	Scotland	Wales
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Medium	Medium	Medium

#### 4.3.4 Looking ahead (I2)

Flooding remains a key priority given the high impact and high-profile nature of its impacts. The evidence base for improved flood defences is mature and the electricity sector has demonstrated

that adaptation measures can be readily implemented. Despite the high costs involved, further action is needed to improve flood defences across the infrastructure sector.

## 4.4. Risks to infrastructure services from coastal flooding and erosion (I3)

Global mean sea levels are currently rising at an accelerating rate. Coastal erosion and coastal flooding, which have always occurred around the UK, will become worse as sea levels rise. Other socioeconomic changes could also increase vulnerability (mainly increased development and population in low-lying coastal areas and decline in salt marshes, shingle and sand dunes which provide an important buffering against coastal flooding and erosion). There is evidence that the consequences of coastal flooding in the recent past have been tempered due to improvements in flood defences, together with advances in flood forecasting, warning and emergency response and spatial planning. However, notable instances of coastal flooding (e.g. in the winter of 2013/14) have still occurred and significantly impacted infrastructure along the coast.

Across the UK, rail networks tend to be exposed to significant coastal flooding, as well as a number of sewage treatment works. Other infrastructure assets tend to have low current and future risk. In the case of nuclear power stations, this is due to their very high standard of protection. Data for levels of risk from coastal erosion are less available, though the CCC has developed projections of risk for England.

There is high confidence that mean sea-level will continue to rise around the UK for at least the next three centuries, even with low climate change scenarios (Palmer *et al.*, 2018). Larger rises are considered possible due to potential marine ice sheet instabilities. Extreme water levels are therefore projected to increase during the 21<sup>st</sup> century and beyond, and without further adaptation (e.g. raising flood defences, managed retreat), the projected increases in extreme water levels will significantly increase coastal flood and erosion risk for railways and some sewage treatments works according to the projections produced for CCRA3. Although shoreline management plans are in place, adaptation responses are currently considered inadequate to fully manage the increasing risk, with further investigation needed. Beneficial actions could include achieving a better understanding of current and future risk, monitoring and evaluation of the projected impact of current policies and actions and the creation of ‘what if’ scenarios of high rates of change.

### 4.4.1. Current and future level of risk (I3)

#### 4.4.1.1 Current risk (I3)

##### 4.4.1.1.1 UK-wide

Coastal flooding and erosion are driven by a combination of the sea level and extreme water levels, which arise as combinations of four main factors: (i) waves (especially setup and runup); (ii) astronomical tides; (iii) storm surges; and (iv) relative mean sea level (Pugh and Woodworth, 2014).



The scale of flooding and erosion is dependent on the characteristics of the land, e.g. underlying coastal morphology (topography, rock type, slope of beach, etc.) and the additional influence of rainfall and river discharge may also be significant in some estuaries (Hendry *et al.*, 2019). These four components exhibit considerable natural year-to-year variability and it is the interaction between the components that combine to result in extreme water levels. Longer-term changes in any, or all, of the four components can also lead to variations in the frequency and magnitude of extreme sea levels. It should be noted that individual components can cause problems on their own, such as flooding caused solely by extreme waves even in places where sea level is not rising.

Global mean sea level (GMSL) increased by 0.16 m from 1902 to 2016 (IPCC, 2019). Relative mean sea levels rose during this period more in the south than north of the UK due to post-glacial rebound (Scotland is rising whereas southern England is sinking), whereas the east coast is more prone to damaging storm surges. This is because of the shallow water depths and funnelling shape of the North Sea, with notable events on 31<sup>st</sup> January and 1<sup>st</sup> February 1953, and 5<sup>th</sup> and 6<sup>th</sup> December 2013 (Spencer *et al.*, 2015; Wadey *et al.*, 2015). However, storm surge risk is also prevalent along the west and south coasts, with noteworthy events on the 26<sup>th</sup> February 1990 and 14<sup>th</sup> February 2014 (Haigh *et al.*, 2017a).

Horsburgh *et al.* (2020) highlight that a growing number of studies, at both global and national scales, have found evidence for increases in extreme still water levels over the late 19<sup>th</sup>, 20<sup>th</sup> and early part of the 21<sup>st</sup> century. The overwhelming scientific consensus is that these observed changes in extreme still water levels around the UK and worldwide have been driven primarily by the observed rise in relative mean sea level. As a result, extreme sea levels that previously had a long return period (>100 years) near the beginning of the 20<sup>th</sup> century now have much lower (~10 year) return periods. There is little evidence for long-term systematic changes in storminess or storm surge magnitude over the last 100 years above natural variability. Several studies have looked at historical changes in the nature of coastal hazards and erosion. Wolf *et al.* (2020) highlighted that it has proved difficult to accurately assess current and historic changes in the wave climate due to the lack of long-term wave measurements and due to the fact that trends are obscured by large natural variability). However, positive regional trends in extreme wave heights have been reported at several locations in the north-east Atlantic since the late 1970s. Haigh *et al.* (2020) reviews studies that have assessed changes in tide. These studies suggest that changes in tidal range will typically be in the order of plus or minus 10% of any changes in mean sea level, which could slightly enhance or lessen coastal flooding at some locations.

Taking a long-term view, Haigh *et al.* (2017b) suggest that the number and consequences of coastal floods appears to have declined since 1915 in the UK, reflecting better defences and improvements in flood forecasting, warning and emergency response and planning. Wider efforts at improved adaptation should also be noted, particularly in recent decades, which has also resulted in a reduction in flood risk. Hendry *et al.* (2019) showed the importance of considering compound events (i.e. flooding from both marine and fluvial/pluvial sources occurring concurrently or in close succession), and that the previous lack of consideration of this has likely led to underestimation of flood risk around UK coasts. The CCC (2018a) highlighted that it is increasingly recognized that natural systems, such as saltmarshes, shingle and sand dunes, provide important buffering against floods and are in decline, which has increased flood risk. These act alongside other natural

infrastructure such as rivers and floodplains to manage flood risk.

As highlighted by Masselink *et al.* (2020), the natural response of coastal systems to mean sea-level rise is to migrate landwards, through erosion of the lower part of the nearshore profile and deposition on the upper part. They highlight that 17% of the UK coast and 19.9% of the Irish coast is currently suffering from erosion. Approximately 3,700 km (around 25%) of the English and Welsh coast is currently experiencing erosion of greater than 10 cm per year.

Sayers *et al.* (2020) quantified the current number of assets or length of infrastructure exposed to a 1:75 chance of annual coastal flooding for major receptors including clean and wastewater sites, electricity generation sites and transport networks (see Table 4.13 below). The assets facing the largest risks from coastal flooding are rail lines, railway stations and sewage treatment works.

**Table 4.13** Number or length of infrastructure assets currently exposed to 'significant' risk of coastal flooding across the UK (Sayers *et al.* 2020)

Infrastructure Asset at 1:75 or greater risk of coastal flooding (present day)	England	Northern Ireland	Scotland	Wales	Total (UK wide)
Water sites (no.)	3	11	0	8	22
Sewage treatment works (no.)	53	0	20	18	91
Power stations (no.)	34	0	1	0	35
Electricity substations (no)	23	0	4	7	34
Rail length (km)	114	20	65	312	511
Rail stations (no.)	5	3	5	12	25
Landfill sites	0	0	0	0	0

Some further risk information by country is given below.

#### 4.4.1.1.2. England

The railway line at Dawlish provides the highest profile example of infrastructure at risk of coastal flooding and erosion. Dawson *et al.* (2016) provide a comprehensive review into the impacts of coastal flooding and erosion at this location. Work is currently underway to further protect this section (see section 4.4.2.1). Yorkshire Water relocating a wastewater treatment works at Withernsea further inland due to coastal erosion. As mentioned in I1, CCRA2 (Dawson *et al.*, 2016) specifically reported on interruptions to the supply of biomass to power stations following flooding of the Port of Immingham in December 2013. Critical power and IT services were lost causing the cessation of operations for a number of days. Tides exceeded the dock gate height by half a metre. Work has been approved to improve flood protection at the Port.

#### 4.4.1.1.3. Northern Ireland

19.5% of the Northern Ireland coastline is suffering from erosion (McKibbin, 2016). DAERA and DfI commissioned a baseline study and gap analysis of coastal erosion risk management in Northern

Ireland. The report identifies areas that may be vulnerable to coastal erosion in Northern Ireland.

#### 4.4.1.1.4. Scotland

CCC (2019c) stated that Scotland has significant infrastructure assets located in coastal areas and hence potentially exposed to flooding from the sea. Key infrastructure assets located in the coastal zone include power stations, ports, roads, and rail networks. According to the Dynamic Coast (National Coastal Change Assessment) project, soft coastline (coasts with the potential to erode) make up 19% (3,800 km) of the Scottish coast. Between a half and a third of all coastal buildings, roads, rail and water networks lie in these erodible sections. Since the 1970s, 870 km of the soft coastline has moved position: 420 km has advanced, 440 km has eroded, and the remaining 2,940 km has remained approximately stable.

#### 4.4.1.1.5. Wales

Welsh railways are particularly exposed with 312 km of rail considered to be at risk (Sayers *et al.*, 2020).

#### 4.4.1.2. Future risk (I3)

##### 4.4.1.2.1. UK-wide

In the UKCP18 marine projections (Palmer *et al.*, 2018), sea levels at the four UK capital cities are projected to rise by between 0.08 m and 1.15 m by 2100, relative to the levels in 1981-2000, depending on location, scenario and level of climate response, excluding vertical land motions. Projected rises are generally higher in the south of the country than the north. In a projection consistent with approximately 4°C global warming by 2100<sup>6</sup>, local sea level rise at the UK capitals ranges from 0.54 m for Edinburgh to 0.78 m for London. Larger rises are possible with higher warming and/or if the sea level responds more rapidly, for example if marine ice sheets were to collapse. The low-likelihood high-impact scenarios have been identified by recent global expert elicitations (Garner *et al.*, 2018; Bamber *et al.*, 2019), which raise the possibility of high global sea level rise under high-emission scenarios, with conceivably reaching 2 m by 2100. There is low confidence in regional projections of storminess and associated changes in storm surges and waves (Palmer *et al.*, 2018).

Brown *et al.*, (2018), drawing on a vulnerability-led and decision-centric framework, developed a Decision Support Tool which combined observations and modelling to explore the future vulnerability to mean sea-level rise and storms for nuclear energy sites in Britain.

##### 4.4.1.2.2. England

Sayers *et al.*, (2020) indicate that the number of rail stations and length of rail exposed to high risk of coastal flooding will increase significantly with climate change in the absence of adaptation. In a

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<sup>6</sup> Based on 50<sup>th</sup> percentile of UKCP18 marine projections, using RCP8.5 concentration pathway.

scenario of 4°C global warming at 2100 (+4°C at 2100) with low population growth, the length of railway track exposed to coastal flooding could potentially increase five-fold in England (400% increase). Sewage treatment works at risk could also increase three-fold (200%), and there is a ~55% increase in risk for electricity substations. Water sites and power stations are projected to have lower risks compared to today in the baseline scenario.

CCC (2018a) estimated the number of infrastructure assets at current and future risk from coastal erosion, as shown below. According to Brand and Spencer (2018), there are 1200 landfill sites in England that are in low-lying coastal areas and almost 80 are likely to start eroding within the next 40 years without intervention.

**Table 4.14** Present day estimates of coastal erosion risk for infrastructure assets in England, taken from CCC (2018c) using values derived from Jacobs (2018). These values do not include erosion rates from complex cliffs.

Infrastructure asset	Present day coastal erosion risk (range from 'mid-estimate' to 'high-estimate')	End century coastal erosion risk (range from 'mid-estimate' to 'high-estimate')
Motorways and A-roads (km)	5 – 6	68 – 93
Other public roads (km)	30 – 49	440 – 602
Railway lines (km)	8 – 12	60 – 76
Railway stations (no.)	0	12 – 15
Historic landfill sites (ha)	21 – 31	181 – 239

#### 4.4.1.2.3. Northern Ireland

Sayers *et al.* (2020) indicates that in the absence of further adaptation and in a +4°C at 2100 scenario with low population growth, the length of railway track exposed to coastal flooding could potentially double in Northern Ireland by the 2080s. The report also notes that rising sea levels pose a significant threat for the coast of NI and climate change could also contribute to beach erosion because of the predicted increase in storm activity and intensity. Projections for other infrastructure assets either do not change in the future or show a decrease in risk.

#### 4.4.1.2.4. Scotland

Sayers *et al.* (2020) indicates that in a +4°C at 2100 with low population growth, the length of railway track (and associated stations) exposed to coastal flooding could increase by around 75% by the 2080s, and rail stations by nearly 30%. Other infrastructure asset types show no change or small decreases in risk in the baseline scenario.

If recent erosion rates were to continue in the future, the National Coastal Change Assessment (Dynamic Coast 1) estimates that by 2050 at least 1.6 km of railway, 5.2 km of road and 2.4 km of clean water network as well as significant areas of runways, would be affected by coastal erosion (Hansom *et al.*, 2017). These numbers are likely to be underestimated. If erosion rates increase in the future, as expected with climate change, Dynamic Coast 1 and National Flood Risk Assessment are likely to underestimate the extent of assets at risk from future coastal erosion. Large numbers of

assets are sited close to potentially erodible coasts (including 1,300 km of roads and 100 km of railway lines). There are assets worth £13.3 billion within 50 metres of the soft coast of which £340 million worth is expected to be threatened by erosion by 2050 (these figures include non-infrastructure assets such as residential and non-residential buildings (CCC, 2019c)). Dynamic Coast 2 will be published in 2021 and will consider how future sea level rise projections will further increase erosion rates and the impacts this could have on assets near the coastline.

#### 4.4.1.2.5. Wales

Sayers *et al.* (2020) indicates that under a +4°C at 2100 scenario, accompanied by a low population growth scenario, the length of railway track (and associated stations) exposed to coastal flooding could increase by around 60% by the 2080s, and rail stations by 10%. Like England, sewage treatment works also show a significant increase in risk of around 50%. Other infrastructure asset types show no change or small decreases in risk in the baseline scenario.

#### 4.4.1.3 Lock-in and thresholds (I3)

Society will experience mean sea-level rise for many centuries even if global temperature is stabilized and so therefore is locked into an increased risk of coastal flooding and erosion if flood defences, for example, are not upgraded. This also creates the potential for lock-in risk for any development in coastal areas, and a particular issue is highlighted for coastal infrastructure, because of the long life-times involved (and the fact it may be costly to retrofit or move later). For instance, new nuclear build is amongst the most extreme type of lock-in (if adaptation were not to be included) with still water return level projections being considered for year 2190 (Horizon Nuclear Power, 2019). High confidence in the projections ensures that sea defences can be engineered to withstand projected rises in mean sea levels, but the high uncertainty makes such decisions difficult, and has led to the greater focus on adaptive management.

There are likely to be certain thresholds in the level and rate of mean sea-level rise that dramatically shift the way coastal flooding and erosion is managed and a point at which infrastructure and properties will be relocated away from the coast (and for current infrastructure, difficult decisions are needed on whether to protect or abandon). However, these thresholds are not well understood for the majority of the coastline. For London, an adaptive management (pathways) approach has been adopted for managing increasing flood risk in the Thames Estuary 2100 Plan (Environment Agency, 2012; Ranger *et al.*, 2013). For sea-level rise below about 2.5 m, with respect to a 2005 baseline, London can be protected via the existing Thames Barrier, along with raising of downstream and upstream defences. However, with a mean sea-level rise of more than 2.5 m, a new barrier with locks would need to be built further downstream to protect London. Hall *et al.* (2019) carried out a sensitivity analysis of the costs and benefits of alternative adaptation pathways to a wide range of mean sea-level rise trajectories for London. They show that the adaptation pathway that most cost-effectively and robustly maintains risk at a tolerable level involves moving the Thames Barrier 17 km towards the sea if mean sea level rises 2 m above present levels. The adaptive flood management approach has been developed into a tool for wider application and is being used elsewhere around the world (Haasnoot *et al.*, 2013, 2019). Frampton *et al.* (2020) considered how adaptation pathways could help strategic coastal management decision-making and adaptation, building on the current

Shoreline Management Planning approach. These iterative adaptive management frameworks use thresholds to determine future management strategies, with additional management strategies, measures or policies aligned to future thresholds levels (adaptation tipping points).

#### 4.4.1.4. Cross-cutting risks and inter-dependencies (I3)

The CCRA3 interacting risks project (WSP, 2020) created a number of systems maps of key interactions between infrastructure, the built environment and natural environment. The maps highlighted a number of interdependencies between coastal flooding and erosion impacts to power, transport and sewage infrastructure leading to knock on impacts to power supply disruptions, transport damage, travel accidents and travel delays.

#### 4.4.1.5 Implications of Net Zero (I3)

There is the potential that some new low / zero carbon energy infrastructure, e.g. carbon capture and storage technology, could be sited in coastal areas. This might require consideration to ensure appropriate siting and climate resilient design.

#### 4.4.1.6 Inequalities (I3)

Sayers *et al.* (2017) showed that compared to the national average, more socially vulnerable communities at the coast are disproportionately at risk and will see their risk increase more rapidly with climate change than elsewhere. As with all flood defences, there are issues with determining what is protected and the associated downside of simply moving the risk elsewhere, and this applies to the services provided by infrastructure as well as direct risks to people from coastal flooding.

#### 4.4.1.7 Magnitude scores (I3)

Present day risk is medium (Table 4.15), as studies since CCRA2 have provided further evidence of the nature and magnitude of observed changes in mean sea-level rise, storms and waves, and associated risks. Quantified evidence on the monetary impact of coastal flooding and erosion on infrastructure is sparse. Although notable events such as the collapse of the Dawlish Sea Wall can cause impacts running into the £10s to £100s of millions, current evidence does not support present day 'high' magnitude at an annual level. The lack of systematic reporting of costs indicates low confidence in this rating, with the possibility that costs are currently underestimated. Sayers *et al.* (2020) and the UKCP18 marine projections (Palmer *et al.*, 2018) indicate that there is high confidence that regional mean sea-level will continue to rise around the UK. Sayers *et al.* (2020) indicate that the number of rail stations and rail length exposed to high risk of coastal flooding will increase significantly with climate change in the absence of adaptation. Coastal erosion is projected to increase the risk to road, rail and landfill infrastructure without further adaptation. Future risk is projected to increase by an order of magnitude in most cases in England. However, despite evidence that risk will rise throughout the UK, as annualised baseline information on the current impact of coastal erosion on infrastructure is not available, it is not possible to determine whether this would be classified as 'high' magnitude. Medium magnitude with low confidence is given for future scenarios (Table 4.15).

**Table 4.15** Magnitude scores for risks to infrastructure services from coastal flooding and erosion

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Medium	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Northern Ireland	Medium	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Scotland	Medium	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Wales	Medium	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

#### 4.4.2 The extent to which current adaptation will manage the risk (I3)

##### 4.4.2.1 Effects of current adaptation policy and commitments on current and future risks (I3)

Many of the policies outlined in risk I2 that relate to all sources of flooding are relevant to this risk also. Additional policies that only apply to coastal flood or erosion risk are provided below.

##### 4.4.2.1.1 England

Shoreline Management Plans (SMP) are in place for the full length of the English coastline. CCC (2018a) noted that while the SMPs provide long-term considerations for all parts of the English coast, they cannot be relied upon as committed adaptation plans as they are non-statutory and unfunded. The Government's July 2020 Policy Statement (HM Government, 2020a) set out the ambition to review national policy for Shoreline Management Plans to ensure local plans are transparent, to continuously review outcomes and to enable local authorities to make robust decisions for their areas (but without further detail on to what extent the SMP aspirations will be funded in the future, which leaves the remaining uncertainty on how far they may be implemented).

To create a more resilient future the Government's July 2020 Policy Statement (HM Government, 2020) set out five policy areas:

1. Upgrading and expanding our national flood defences and infrastructure,
2. Managing the flow of water more effectively,
3. Harnessing the power of nature to reduce flood and coastal erosion risk and achieve multiple benefits,
4. Better preparing our communities,
5. Enabling more resilient places through a catchment-based approach.

#### 4.4.2.1.2 Northern Ireland

The Northern Ireland Climate Change Adaptation Programme 2019-24 mentions plans by Translink to complete a study on the effects of expected mean sea-level rise on coastal assets using UKCP18 to inform long term decisions on its management of track assets (DAERA, 2019).

#### 4.4.2.1.3 Scotland

SMPs are in place in some parts of Scotland that have coastlines that are vulnerable to coastal flooding or erosion. SEPA have not yet met their requirement under S19 of the FRM Scotland Act to map artificial features and natural structures which could impact flood risk if removed. These plans are currently being reviewed.

The Scottish Government have also commissioned the Dynamic Coast project to deliver an up-to date assessment of coastal changes and provide a robust evidence base from which to plan strategically. Dynamic Coast 2 will be published in 2021 and will consider how future sea level rise projections will further increase erosion rates and the impacts this could have on assets near the coastline. The project supports existing strategic planning, such as SMPs, Flood Risk Management Planning, Strategic and Local Plans, and National and Regional Marine Planning, and identifies those areas which may remain, or may become, susceptible to erosion in the coming decades and require supplementary support. The identification of such susceptible areas and assets will enable the development of future management policies and adaptation plans that are robustly based on a strategic and objective evidence base.

#### 4.4.2.1.4 Wales

SMPs are in place for the full length of the Welsh coastline. The Welsh climate change adaptation plan, *Prosperity for All: A Climate Conscious Wales* (Welsh Government, 2019b) notes that Coastal Alert System which forecasts coastal flooding, wave overtopping, and toe scour up to 36 hours in advance. A number of other projects are also underway with Network Rail to improve the resilience of the rail network in Wales. Much of these works are being undertaken to respond to a number of impacts including flood risk and risks from slope and embankment failure. Network Rail has also invested £50 million along the north Wales coast under their railway upgrade programme. The Welsh Adaptation Programme highlights this as one of the key actions to help address coastal risks, including that innovative technologies are being used to help reduce the risks to rail lines on soft coastal ground.

In the National Strategy, the Welsh Government prioritises FCERM funding to schemes which primarily reduce risk of flooding or coastal erosion to existing homes. While it states infrastructure



(and businesses) may also benefit, especially in larger schemes, additional costs or protection to third party assets must be subject to a partnership contribution proportionate to those assets benefitting. A number of significant projects have been completed since CCRA2. For example, the £3m Town Beach scheme in Porthcawl, completed in 2019, upgrades the original defence and was designed to reduce risk from flooding and erosion to 260 properties including multiple businesses and key infrastructure along the promenade.

#### 4.4.2.2 Effects of non-government adaptation (I3)

The CCC (2019b) reported that the electricity sector has a well-developed understanding of risks faced by flooding including coastal flooding. Planned actions by electricity supply, transmission and distribution companies are expected to see over 90% of substations deemed at risk of flooding become resilient to 1 in 1000-year flood events by 2021. This is in line with standard ETR 138, which applies this requirement to primary substations with over 10,000 connections. This standard includes an assessment of the risks from flooding to all new and existing sites. It is not clear what actions are being taken for non-primary substations. It was reported that plans to manage risks to nuclear infrastructure include consideration of all relevant hazards. The entire nuclear fleet of power stations is located in the coastal zone, with the Office for Nuclear Regulation expecting nuclear licensees to provide flood protection to a return period of 10,000 years. Nuclear sites thus have very high standards of protection.

Resilience standards for ports are left to individual asset owners. It was reported that ports have been proactive in raising quay heights and assessing interdependencies. It is stated that there is no overarching plan to adapt ports to manage climate risks (CCC, 2019a). Internationally, there is non-mandatory guidance from the World Association for Waterborne Transport Infrastructure or PIANC (Working Group 178) regarding climate change adaptation for ports and inland waterways.

The CCC (2019b) states that there is no clear plan or process by the industry or Government with actions to manage climate risks – including coastal flood risk – to telecoms, digital and ICT infrastructure.

Some adaptation is underway to protect vulnerable coastal rail infrastructure. Dawson *et al.* (2016) assessed the extent to which projected sea-level rise would have been likely to impact upon the functioning of the Dawlish to Teignmouth stretch of the London to Penzance railway line, in England, in the absence of improvements to the sea wall. The critical Dawlish line was projected to suffer serious reliability issues due to flooding by 2040 on the basis of no additional action, with line restrictions increasing from 10 days per year to 30–40, and maintenance costs tripling or quadrupling (£6.9–£8.7m per year, including over £1m compensation). A higher and more resilient sea wall is currently under construction.

#### 4.4.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I3)

The available evidence indicates that the risk is beginning to be managed through the various policy frameworks (e.g. SMPs, FCERM) and that understanding of the risk has improved through projects such as Dynamic Coasts (Hansom *et al.*, 2017). Infrastructure owners with the most risk have also

been proactive in protecting their assets. However, it is difficult to ascertain with any confidence whether, despite the investment in the area, the level of risk is being maintained to today's level.

Although policy frameworks exist, further work is needed to translate these into delivery. This applies to all nations of the UK. Several barriers exist, which prevent both private and public operators from undertaking the appropriate level of adaptation to coastal risk and therefore typically require government intervention, either through information, incentives, regulations or in some cases directly providing adaptation (see discussion for previous risk). Another barrier can occur where there is disagreement over responsibility when adaptation is needed, for example where different infrastructure operators, such as road, rail and water, are at risk at potentially different time horizons as reported in Old Colwyn, Wales (BBC, 2019).

#### 4.4.2.4 Adaptation Scores (I3)

<b>Table 4.16</b> Adaptation scores to risks to infrastructure services from coastal flooding and erosion			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)

#### 4.4.3. Benefits of further adaptation action in the next five years (I3)

##### 4.4.3.1 Additional planned adaptation that would address the adaptation shortfall (I3)

There is increased realisation that it is unrealistic to promote a 'hold the line' policy for much of the coastline. The CCC (2018a) highlighted that 1,460 km of coastline in England designated as 'hold the line' to the end of the century, achieves a much lower benefit-cost-ratio than the flood and coastal erosion risk management interventions that are government-funded today. On this basis therefore, funding for these locations is unlikely and realistic plans to adapt to the inevitability of change are needed now. This raises the fundamental questions of how to: (i) plan our future shoreline on the open coast and along estuaries; and (ii) deliver practical portfolios of adaptation options that are technically feasible, balance costs and benefits, can attract appropriate finance, and are socially acceptable.

Recent research commissioned by the CCC (Jacobs, 2018) has explored the application of adaptation pathways to help explore alternative sequences of adaptation responses to climate change at a sample of coastal sites. The process of developing and evaluating alternative adaptation pathways allows potentially flexible responses to be explored in the face of uncertainty. As noted earlier, there are significant uncertainties inherent in estimating the rate of mean sea-level rise and the future frequency and severity of extreme coastal events that drive coastal erosion and flooding. The use of adaptation pathways for the long-term planning of flood risk management, first used in developing the Thames Estuary 2100 flood risk management strategy (Environment Agency, 2012), has been shown to be a promising technique that is being applied more widely (e.g. in developing the Humber 2100+ flood risk management strategy). The Environment Agency committed to increase use of

adaptive management in flood and coastal risk management (Environment Agency, 2020a). As mentioned earlier, Hall *et al.* (2019) quantify sequences of adaptations that would be needed to protect London from flooding by the sea to the year 2300. The approach is transferable to other vulnerable coastal cities of high strategic, economic and political importance.

Much of the work required in this area revolves around better understanding risk. Firstly, comprehensive data on the scale of risk from coastal erosion and flood risk for roads, ports and airports are required for future climates. Secondly, better monitoring and evaluation of existing policies would be beneficial to determine to what extent these are managing the risk down (such as with the risk of flooding to rail). Given the uncertainties around sea level rise, 'what if' planning for high coastal risk scenarios would be beneficial for understanding what could be done in the event of very high rates of change.

#### 4.4.3.2 Indicative costs and benefits of additional adaptation (I3)

In general terms, the literature reports that coastal adaptation is an extremely cost-effective response, significantly reducing residual damage costs down to very low levels (Hinkel *et al.*, 2014). The National Infrastructure Commission (2018c) analysed the investment that would be required to provide a range of resilience standards for coastal flooding. The benefits of achieving a resilient infrastructure sector were estimated as the value of the 'avoided' or 'mitigated' damage and disruption caused by climate-induced events. Similar analysis was undertaken by the Environment Agency (2014), updated in Environment Agency (2019b), who estimated that the net present value of the optimised long-term investment in flood and coastal erosion risk protection, including the economic damages avoided by making the investment, including the benefits of protecting infrastructure.

#### 4.4.3.3 Overall urgency score (I3)

As a result of the medium projected magnitude for this risk, and the view that current and announced adaptation is partially managing risk, it has been scored as further investigation needed. Beneficial actions could include achieving a better understanding of current and future risk, monitoring and evaluation of the projected impact of current policies and actions and the creation of 'what if' scenarios of high rates of change. Further investigation is needed to identify the locations where more action would be beneficial to infrastructure and the equivalent built environment.

**Table 4.17** Urgency scores for risks to infrastructure services from coastal flooding and erosion

Country	England	Northern Ireland	Scotland	Wales
<b>Urgency score</b>	Further Investigation	Further Investigation	Further Investigation	Further Investigation
<b>Confidence</b>	Medium	Medium	Medium	Medium

#### 4.4.4. Looking ahead (I3)

Further work would be beneficial on interacting risks, particularly to infrastructure services from coastal, river (fluvial), surface water (pluvial) and groundwater flooding. As stated, Hendry *et al.* (2019) showed the importance of considering compound events (i.e. flooding from both marine and fluvial/pluvial sources occurring concurrently or in close succession). The previous lack of consideration of compound flooding means that flood risk has likely been underestimated around UK coasts, particularly along the south-western and western coasts. Further work could also assess more fully the interaction between flood and erosion risk (Dawson *et al.*, 2009; Pollard *et al.*, 2019) and consider multi-hazard risk more widely (i.e. account for interaction between flooding, and other hazards, such as wind damage or landslides (Zscheischler *et al.*, 2018; Hillier *et al.*, 2020)). It is crucial that this be addressed in future assessments of flood risk and flood management approaches.

### 4.5 Risks to bridges and pipelines from flooding and erosion (I4)

Since CCRA2, limited new evidence has been published on the risk to bridges and pipelines from flooding and erosion. The lack of significant evidence for bridges indicates no overall change in the magnitude of impacts for this descriptor. Currently, there are no quantitative projections for climate change impacts on these assets with results limited to the identification of weather events and environmental hazards which underlie the risk (e.g. rainfall, temperature, erosion for pipelines, increased hydrostatic pressure, scour for bridges).

Overall, the current risk to bridges and pipelines from flooding and erosion is identified as medium, with medium confidence; for future scenarios, the risk remains medium but with low confidence. Although, there have been positive developments in all UK nations to improve understanding of the risks to bridges and pipelines from scour, flooding and erosion, more work is still needed to understand the extent of assets at risk, the amount of adaptation underway and how the risk is being reduced through those actions. Further research is needed to define links between the forecasts and the actual projected impact at the local, regional and national environment level; i.e. the level of rainfall, frequency of severe events, changes in wind climate, the degree, extent and depth of flooding, increased rates of erosion and the exacerbation of land movement. A greater understanding and analysis of ground movement and associated impacts is another area requiring further investigation.

The Urgency Score highlights the need for further investigation for the whole UK, given the low quality of available evidence. This should concentrate on systematically assessing and quantifying the extent to which current plans will reduce risk to a low magnitude across the likely range of future climate scenarios (2 – 4°C, and across the 10-90<sup>th</sup> percentile uncertainty range within each scenario).

## 4.5.1 Current and future level of risk (I4)

### 4.5.1.1. Current risk (I4)

Note: it has not been possible to split the evidence by UK country for this risk.

#### 4.5.1.1.1. UK-wide

The main categories of weather events and environmental hazards for pipelines include flooding and heavy rainfall (including saturated ground conditions), snow and ice, increases in temperature, coastal and river erosion, storm events, and high winds. Since the last CCRA, specific publications addressing risks to pipelines from climate change have been scarce.

The literature for bridges is more established than pipelines. Ettema *et al.* (2018) report that in 2016 (post Storm Desmond), 452 critical transportation assets were remediated, including 278 bridge repairs at an estimated cost of £123.6m over four years in Cumbria County Council. This adds to evidence of the impact of floods on bridges reported in CCRA2, such as the 2009 Cumbria floods, where several bridges were lost, and the 2015 winter floods where a major bridge connecting the town of Tadcaster collapsed, causing major transport disruption and the rupturing of gas pipelines and loss of fibre optics communications. It appears there has been a trend of increased frequency of extreme rainfall causing increased failure incidence of old masonry arch bridges.

In recent times the failure incidence of such short-span bridges has been noticeably increasing (e.g. in November 2009, three 19<sup>th</sup> century UK bridges failed) and could be suggestive of insufficient hydraulic capacity or alternative failure mechanism not envisaged at the time of design, such as foundation scour or undermining (Ryan *et al.* 2015).

Sayers *et al.* (2015) stated that factors contributing to collapse of bridges include high river flows due to rainfall and debris stuck against piers, and more frequent high in-river water levels. Scour of the bridge foundations is well-known to be the first factor for bridge failure. Warmer temperatures may lead to drying out of embankments and accelerated weathering-related deterioration. Although work has been conducted for resilience assessment on the UK Gas Distribution Network (ENA, 2015), the lack of significant evidence in changes to the current risk for bridges would indicate no overall change in magnitude for this descriptor.

Lamb *et al.* (2019) developed a combined scour fragility and statistical bridge failure to quantify the risk of disruption due to scour over the British rail network (using 1830-2003 data). Models are used to estimate the probability of single or multiple bridge failures on the rail network of Great Britain. These are combined with a model for passenger journey disruption to calculate a system-wide estimate for the risk of scour failures incorporating passenger journey disruptions and economic costs. Without considering climate change, this estimate can be translated into an expected annual utility cost to passengers of between £6 million and £60 million. However, the model may be adjusted to consider climate change scenarios, by reflecting changes in the hydrological regime.

This magnitude of risk to bridges and pipelines from flooding and erosion may vary between

different types of places (e.g. urban, rural, upland, and coastal according to the exposure and vulnerability of the bridge, encompassing bridge design and material). For example, rural bridges tend to be smaller than urban bridges (due to the minor demand), however they are likely to have less redundancy, i.e. no alternative way is available to cross the obstacle.

#### 4.5.1.2. Future risk (I4)

##### 4.5.1.2.1 UK- wide

CCRA2 (Dawson *et al.*, 2016) stated that increased winter precipitation and river flows will increase scour at bridges, potentially increasing the rate of failure to an average of one bridge per year in the UK. At the time, there had not been any national-level modelling of how risk may increase in the future. It was also reported that significant uncertainties about the structural integrity of road and rail bridges existed (many of which were built over a century ago). It was not known at a national level which bridges were used for gas pipelines/electricity cables (although it was stated that service providers have this mapped at the local level).

The availability of data is currently a missed opportunity, since bridge data are scarce or not well-organised, particularly at national level (Pregnotato *et al.*, 2019). Regarding strategic crossings and pipelines in general, data are protected due to security.

Currently, there are no quantitative projections for climate change impacts for pipelines. Further research is needed to define links between the forecasts and the actual projected impact at the local, regional and national environment level, i.e. the level of rainfall, frequency of severe events, change in wind levels, the degree, extent and depth of flooding, increased rates of erosion, and the exacerbation of land movement. A greater understanding and analysis of ground movement and associated impacts is another area also requiring further investigation.

Bridges have considerably long service lives and are usually built to a design life of 50-100 years. However, existing bridges were built with past climate as their basis, with no consideration of climate change. Nasr *et al.*, (2019) present the most comprehensive work on the potential risks on bridges as a result of climate change. Utilising more than 200 research articles, a total of 31 individual risks are identified and discussed, including durability, serviceability, geotechnical, increased demand, accidental loads, extreme natural events, and operational risks. Most of these risks may act in combination to cause bridge failures. For instance, the increased hydrostatic pressure behind bridge abutments can combine with the risk of accelerated scour rates and the durability risks to cause failure.

The Rail Safety and Standards Board (RSSB, 2016a) describe the potential impact of future climate change on the GB railway. Excess precipitation and flooding can potentially lead to earthworks failure and scour of bridges. UK transport agencies (e.g. Highways England, Network Rail) are in the process of reviewing current standards, as an input to the design process (e.g. the on-going Network Rail climate change adaptation plan). Bridge scour is controlled based on the design, using a 1 in 200-year return period rainfall event for new construction, with a 20% allowance for climate change. Similarly, new drainage systems are designed based on a return period storm event of 10 to 50

years, with a 20% allowance for climate change (Network Rail, 2015b; Highways England, 2016). However, guidelines address the peak river flow allowances by river basin district with much higher values (from 20% up to 105% for 2080s). Thus, the design in respect of bridge scour being based on a 20% single national allowance for climate change does not seem appropriate (i.e. +20% likely to be readily exceeded in future scenarios) (Reynard *et al.*, 2009) nor in keeping with current climate evidence (e.g. the Environment Agency is in the process of updating peak river flow allowances by river basin district, based on UKCP18) (Environment Agency, 2020b). Overall, there is much debate about the 20% uniform adjustment in estimated peak flood flows (Kuklicke and Demeritt, 2016; Pregolato *et al.*, 2017), since on one hand it is considered ‘simplistic’ (catchment type variability or regional variations ignored) (Reynard *et al.*, 2009; Defra, 2006), but on the other hand it is a pragmatic approach which allows management decisions to be made (Lane *et al.*, 2011).

Ongoing urbanisation of the watershed is indicated as a cause of increased levels of flooding, which has been cited by multiple studies as a potential factor that could exacerbate risk, especially of short-span bridges over relatively small waterways (e.g. small rivers, streams and canals), which were usually designed for relatively minor values compared to the standard return-period floods.

No systematic quantitative assessment of climate risks to bridges for the UK exists, unlike for the United States (e.g. Wright *et al.* (2012) and Khelifa *et al.* (2013)), hence it is not possible to adequately assess the differences in risk between devolved administrations in detail. Updated climate projections can support risk judgements regarding the weather and climate variables that underpin risks to bridges, i.e. heat-induced damage to pavements and railways, as well as thermally-induced stresses in the structure, melting permafrost that generates additional runoff and sea level rise, thus higher flow speeds and faster scour at piers, rainfall events that trigger slope failure, foundation settlement and landslides, seasonal contrasts of rainfall to generate shrinkage and swelling of clays, and winds that generate wave impact to piers and abutments (Amro Nasr *et al.* 2019). Overall, there is no evidence to suggest that the magnitude of the risk has changed for this descriptor since CCRA2.

#### 4.5.1.3 Lock-in and thresholds (I4)

Bridges are critical components of transportation networks and have clear potential for lock-in risks, with design lives of 50-100 years. They are also extremely expensive to retrofit, so correct specification is essential. There are a large range of specific thresholds associated with bridge design, notably with the engineering to cope with floods or windstorms of specific return periods. Given likely increases to extremes, this will require increases in engineering codes. However, this is challenging for new bridges because of uncertainty, and the balance between the level of climate uplift to factor in versus the additional costs of doing so.

#### 4.5.1.4 Cross-cutting risks and inter-dependencies (I4)

In terms of interacting risks, bridges often co-locate various types of infrastructure (e.g. pipes, electric cables) that cross a river at the same point. Also, both bridges and pipelines are affected by road transportation. Extreme weather impacts on the ability of the workforce to access and carry out their roles, particularly field-based engineers. The CCRA3 interacting risks project (WSP, 2020)

identified the impacts which have the greatest number of upstream connections (i.e. have the greatest potential for cascading failures throughout the infrastructure system and wider economy). Transport infrastructure damage is in the top 20 impacts with 3 connections.

WSP (2020) noted that the impact of flooding on transport infrastructure can have a number of significant cascading impacts in the 2020s, 2050s and the 2080s.

- The direct impact of extreme rainfall events causes flooding of transport infrastructure and hubs.
- Indirect impacts of cascades from flooding of infrastructure leading to transport damage and subsequent travel accidents and travel delays. The latter cascade was rated as having a medium risk in 2020 and a high risk (based on likelihood and impact) in 2080 under a 4°C scenario.
- Cross- sectoral, increased drought stress in the natural environment can lead to soil desiccation, impacting soil condition and quality. This can lead to structural stability issues and pipeline movement.

It is important to note that transport networks (especially roads) are critical during emergency management and recovery, allowing accessibility to hospitals and to sites for repairs and replacements (e.g. Arrighi *et al.*, 2019).

Bridges also represent an important connection between infrastructure and cultural heritage and provide examples of interactions with risks discussed in Chapter 5 (Kovats and Brisley, 2021). There are implications to the need for maintenance, and potentially poor maintenance for historic bridges, which then suffer during severe weather. For example, the collapse of parts of the Grade-II listed Tadcaster Bridge caused by the swollen River following Storm Eva in December 2015 (Historic England, 2016).

#### 4.5.1.5 Implications of Net Zero (I4)

There is no clear evidence that the UK's Net Zero target will significantly affect this risk. It is stated in the CCC Net Zero Technical Report (CCC, 2019a) that the UK's gas distribution networks are currently undergoing a programme of refurbishment that is replacing existing iron gas distribution pipes with plastic ones that will potentially make the networks 'hydrogen ready'. This replacement programme will need to consider future climate risks. The CCC's Sixth Carbon Budget advice suggested that parts of the gas grid may need to be decommissioned as part of a transition to Net Zero, meaning the future gas grid may not be as extensive as the one we have today. It will be necessary to assess any change in risk that this may pose. Climate change (warming temperatures) will affect UK energy demand for heating, and thus have implications for gas or hydrogen demand, see Risk H6.

#### 4.5.1.6 Inequalities (I4)

There are no national assessments on bridge or pipeline risk which can be used to discuss observed inequality of current risk in relation to individual, place and region. However, past episodes have evidenced equality issues in crossing. For example, Workington had different services on two sides of the river (e.g. one supermarket on one side only) and in 2009 a bridge failure required extensive round



trips to the nearest crossing. Bridge failures elsewhere are unlikely to be as impactful (e.g. in Newcastle city centre there are 8 bridges to cross the River Tyne, and large services on both river sides). To better assess this, the DfT Resilience Review (2014) established the need to identify critical single points of failure in the transport network which have potentially high impacts for society and economy (and the potential to isolate remote communities) as a key priority.

#### 4.5.1.7 Magnitude scores (I4)

**Table 4.18** Magnitude scores for risks to bridges and pipelines from flooding and erosion

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	Medium	Medium	Medium	Medium
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Medium	Medium	Medium	Medium	Medium
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Medium	Medium	Medium	Medium	Medium
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Medium	Medium	Medium	Medium	Medium
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

The evidence supports a medium magnitude current risk for flooding and erosion on bridges and pipelines for all nations of the UK (Table 4.18). It is clear that bridges, long-life infrastructure built with past climates as their basis, are vulnerable to current hazards. This has been evidenced through previous catastrophic failures such as the 2009 Cumbria floods and the loss of the Tadcaster Bridge in 2015 (which also ruptured gas lines). Remediation costs in Cumbria cost £123.6 million over a four-year period (Ettema *et al.*, 2018). Annual expected costs associated with passenger delays from bridge scour across Network Rail's network have been estimated at between £6 million and £60 million (Lamb *et al.*, 2019). The literature on equivalent risks to pipelines is less well-established than for bridges, although it is noted that these infrastructures are often co-located. The authors give medium confidence in this assessment, whilst acknowledging that less evidence is available for pipelines.

The evidence also supports medium magnitude for future risk with low confidence across all future

climate scenarios in this assessment for the four countries of the UK. Increased winter precipitation and river flows will increase the scour hazard for bridges, and hence sustain or increase expected impacts above current levels. Vulnerability of bridges is an issue, with many built over a century ago. Currently there are no quantitative projections for climate change impacts for pipelines. The lack of quantitative studies on future impacts on bridges and pipelines means this assessment is given with low confidence.

#### 4.5.2 The extent to which current adaptation will manage the risk (I4)

##### 4.5.2.1 Effects of current adaptation policy and commitments on current and future risks (Risk I4)

###### 4.5.2.1.1 England

Highways England addressed risks posed by climate change for the first time with the Climate Change Adaptation Progress Update (Highways England, 2016). They also updated the Design Manual for Roads and Bridges (DMRB), a series of standards, advice notes and other documents for the design, assessment and operation of roads in the UK, by including the document “LA114 Climate Change”, which sets out the effects of climate on highways (climate change resilience and adaptation), and the effect on climate of greenhouse gas emissions from construction, operation and maintenance projects (Highways England, 2019). Highways England’s climate risk assessment identified vulnerabilities in its network using a scenario at the upper end of the range defined as the CCRA3 pathway to 4°C global warming at the end of the 21<sup>st</sup> Century<sup>7</sup>. It used this assessment to update operational procedures and adaptation plans. The actions reported in NAP2 focussed particularly around flood risk, slope stability and bridges, with HE reporting that 95% of the network is in good condition, although this is not necessarily a true indication of the ability for roads to operate in hazardous conditions. The CCC Progress Report noted (2019b) that work is ongoing to improve understanding of the risk to gas networks crossing bridges.

###### 4.5.2.1.2 Northern Ireland

Northern Ireland’s Climate Change Adaptation Programme 2019–2024 (DAERA, 2019) refers to the DMRB and states the Department for Infrastructure is contributing to the review and update of the Manual which will take into account the latest climate change projections from UKCP18.

###### 4.5.2.1.3 Scotland

The Scottish Ministers’ High Level Output Specification, Control Period 6, sets out how investment strategies must ensure enhanced network resilience from adaptation interventions. Scottish Ministers require Network Rail to develop and apply suitable Key Performance Indicators to monitor the impact and mitigation of climate change on network disruption. This is intended to provide the means to measure the benefits of adaptation interventions.

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<sup>7</sup> The 50<sup>th</sup> percentile of the UKCP18 probabilistic UK projections with RCP8.5 emissions. The 50<sup>th</sup> percentile of the UKCP18 global projections reaches 4.2°C warming at 2070-2099 with RCP8.5 emissions. See Chapter 2 (Watkiss and Betts, 2021) for further details.

For roads, the Second Scottish Climate Change Adaptation Programme (Scottish Government, 2019b) states that Transport Scotland will be undertaking the Second Strategic Transport Projects Review (STPR2). STPR2 will identify strategic transport infrastructure interventions. Transport Scotland implemented the Scour Management Strategy and Flood Risk Emergency Plan in 2018 across operating companies and Design-Build-Finance-Operate providers aimed at providing enhanced monitoring of trunk road bridges and other structures that are at risk.

#### 4.5.2.1.4 Wales

The Welsh Government's climate adaptation plan, A Climate Conscious Wales (2019b) stated that more research is needed to identify the number of bridges at risk of bridge scour now and in the future, as well as the amount of adaptation underway nationally. The report mentions this would assist in enabling better decisions over the next 5 years (many actions may have long lead times such as relocating or rerouting bridges). They mention work is already underway with the British Geological Survey to discuss future research into fluvial scour; 1,000 listed and scheduled bridges have been mapped, with all bridges on the strategic road network having been risk-assessed and prioritised for scour repairs. More generally, Wales and West Utilities (working with Landmark Information Group) have developed an infrastructure vulnerability mapping tool (using sea level rise inundation, new tidelines, tidal flooding and fluvial flooding for different emission scenarios and probabilities). This includes potential bridge impacts and transport infrastructure impact.

#### 4.5.1.2 Effects of non-governmental adaptation (I4)

The GB railway network is managed by Network Rail. Bridge scour is considered at the design stage and is based on a 1 in 200-year return period rainfall event for new construction, with a 20% allowance for climate change (RSSB 2016a). The CCC Progress Report (2019a) stated that Network Rail have deemed 181 bridge sites to be at an intolerable risk of bridge scour according to information from Network Rail (provided via personal correspondence). Standards require the risk of these assets to be reduced within two years of the bridge being assessed. Similarly, new drainage systems are designed based on a return period storm event of 10 to 50 years, with a 20% allowance for climate change. Moreover, the Network Rail Weather and Route Climate Change Adaptation plans contain actions based around preparing for a 4°C global temperature scenario (although these are based centred on preparation, rather than specific measurable goals to reduce risk).

#### 4.5.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I4)

As summarised above, there have been positive developments in all UK nations to improve understanding of the risks to bridges and pipelines from scour, flooding and erosion, however more work is still needed to understand the extent of assets at risk, the amount of adaptation underway and how the risk is being reduced through those actions. As there is no evidence base assessing the effects of future adaptation in managing the risk, this assessment must be given with low confidence.

## 4.5.2.4 Adaptation Scores (I4)

<b>Table 4.19</b> Adaptation scores to risks to bridges and pipelines from flooding and erosion			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

## 4.5.3. Benefits of further adaptation action in the next five years (I4)

## 4.5.3.1 Additional planned adaptation that would address the adaptation shortfall (I4)

For pipelines, the Energy Network Association (2015) stated improving drainage in areas that regularly flood during extreme weather events is one strategy of adaptation; monitoring of river and coastal erosion, as well as the development of flood, coastal and updated contingency defence measures as further strategies. Pipeline operators may be forced to follow new land zoning codes or adaptation measures such as re-routing lines from high-risk areas, and structural upgrades to existing infrastructure.

For bridges, Nasr *et al* (2019) found that scour depth can be reduced by streamlining abutments by means of wing walls, and piers by means of cutwaters. Alternatively, the use of stone pitching to armour the riverbed around abutments and piers is a very effective way to prevent scour. Reforming maintenance and inspection manuals should accommodate the effects of climate change, e.g. through a revision of the design codes to account for the effects of climate change, specifically in relation to bridge foundation scour and the effects of increased wetting and drying of soils in which pipelines are buried. Mitigation methods suggested include new protocols of maintenance and early-warning systems, however more data are needed to support this direction of development. Sayers *et al.* (2015) state that the most significant adaptation is likely to come through changes in maintenance operations, improving collaboration with emergency managers, recognising emergency management as an integral function of managing infrastructure.

## 4.5.3.2 Indicative costs and benefits of additional adaptation (I4)

The costs of adapting pipelines and bridges to climate change are very site-specific, and costs vary significantly between adapting the current stock versus new infrastructure. There is some older literature on the costs of adaptation for bridges (road and rail bridges) to address scour risk (Nemry and Demirel, 2012), which includes estimates for the UK and Ireland where annual costs are estimated at €47 million/year in the 2050s. Of these costs, 80% are for road and 20% for rail bridges. This is reported at approximately 2% of current road maintenance costs. The benefits of adaptation – in terms of avoided scour, possible failure, and subsequent repair or reconstruction (and indirect effects include travel time losses) – were not assessed, though the costs of any failures are normally large.

Bridges and tunnels have a long service life which makes them priority assets for adaptation. Lamb *et al.* (2019) considered the economic costs of bridge failures due to scour over the Great British rail network, including travel time costs, estimating the annual risk (expected annual utility cost to passengers, but excluding freight and speed restrictions when scour damage is suspected) of between £6 million and £60 million. This provides some baseline costs, onto which future climate risks will act, and adaptation could reduce. The Tomorrow's Railway and Climate Change Adaptation (TRaCCA) programme did look at options for the rail network overall to adapt in the most cost-effective way, with some quick wins suggested, although for scour this focused on better vulnerability information (RSSBa, 2016).

For the road network, Atkins (2013a) looked at the potential risks of climate change on road bridges for the Highways Agency (but considered all risks, not just scour). This looked at reduced service life, additional maintenance and associated lane closures, and found the benefits of adaptation were similar to costs for central scenarios (with benefit to cost ratios close to one) but BCRs rose significantly under worst case scenarios.

#### 4.5.3.3 Overall urgency scores (I4)

**Table 4.20** Urgency scores risks to bridges and pipelines from flooding and erosion

Country	England	Northern Ireland	Scotland	Wales
<b>Urgency score</b>	Further investigation	Further investigation	Further investigation	Further investigation
<b>Confidence</b>	Low	Low	Low	Low

There have been positive developments in all UK nations to improve understanding of the risks to bridges and pipelines from scour, flooding and erosion and actions are being taken to reduce vulnerability. However, as future risk has been assessed as medium with limited evidence on the extent to which current and announced adaptation will manage the risk, Further Investigation scores have been assigned to each of the four UK countries (low confidence). There is a need to concentrate on systematically assessing and quantifying the extent to which current plans will reduce risk to a low magnitude across the CCRA range of future climate scenarios (2°C and 4°C global warming by the end of the century, and across the 10<sup>th</sup> - 90<sup>th</sup> percentile uncertainty range within each scenario) or whether more action is needed to achieve this.

#### 4.5.4. Looking ahead (I4)

Identification and prioritisation of actions would benefit from a national assessment of bridge and pipeline risk. In terms of the railway sector, the CCC Progress Report argues that although delay data is of interest, as an impact indicator it does not give a sense of how vulnerability or exposure to climate risk is changing. They argue for better information on asset, slope and embankment condition and exposure, as well as the standards of new adaptation interventions. It is necessary to assess any potential change in risk brought about by the replacement of existing iron gas distribution pipes with plastic ones that will potentially make networks 'hydrogen ready' in a Net Zero context.

## 4.6. Risks to transport networks from slope and embankment failure (I5)

Increased incidence of high rainfall combined with preceding periods of desiccation and cracking are expected to lead to an increase in incidents of slope failure within the transport network. This conclusion is consistent with the evidence reviewed for CCRA2. Rainfall is seen as the main trigger of deterioration of the mechanical and hydraulic properties of engineered fill forming infrastructure slopes, especially considering wetting-drying and freeze-thaw cycles. Extreme weather is expected to increase the rate of these deterioration processes, however the publications reviewed suggest that these deterioration processes are not yet fully understood.

Underpinned by the 2020 Stonehaven derailment, the current risk magnitude score is medium (low confidence); for future scenarios, the risk magnitude is also medium (low) confidence. The urgency score for the whole of the UK indicates that more action is needed, although the confidence is low (e.g. deterioration methods are not fully understood) and it is difficult to ascertain whether current adaptation approaches are sufficient. Adaptation methods presently focus on providing improved numerical tools for infrastructure asset owners to predict failure occurrence. Improved instrumentation and monitoring systems is seen as promising for the understanding of slope failure processes in relation to meteorological conditions. However, additional work on the characterisation of engineered soil assets can also assist with understanding of the spatial distribution of risk.

### 4.6.1 Current and future level of risk (I5)

Note: it has not been possible to split the evidence by UK country for this risk.

#### 4.6.1.1. Current risk (I5)

Slope deterioration and resultant failures have a significant negative impact on transport networks both in the UK and internationally. An important driver for this loss of performance is weather-driven annual cycles of pore pressure, and extreme weather is indicated as a potential factor contributing to the occurrence of failure. In the context of the potential impact of climate change, various works are studying a number of challenges, e.g. differences in initial asset condition related to historic construction techniques and hence baseline performance, or differences in age and hence the number of seasonal cycles that have contributed to asset deterioration.

CCRA2 (Dawson *et al.*, 2016) reported that there are 20,000 km of engineered cuttings and embankments supporting the UK's transport infrastructure. Older, less well compacted earthworks such as those supporting the rail network are deteriorating at a faster rate than newer earthworks built to more modern construction standards. In England and Wales, 5% of earthworks (embankments, cuttings and rock cuttings) were classed as being in a poor condition in 2012/13, with a further 48% classed as being in a marginal condition. There were, on average, 67 earthwork failures a year across the rail network between 2003/04 and 2013/14, of which 55 were in England and Wales and 12 in Scotland. There were some significant fluctuations during this period, with 107 failures in 2007/08 and 144 failures in 2013/14. The Western region has the highest average number

of failures (14 per year between 2004/05 and 2012/13). The busy West Coast and East Coast lines averaged 9 and 7 failures a year respectively. CCRA2 also reported that increased incidences of natural and engineering slope failure affecting the road and rail network in the winters of 2012/2013 and 2013/2014 demonstrate their vulnerability to the type of intense rainfall events that are expected.

Recent studies are consistent with the evidence reviewed for CCRA2. Increased incidence of high rainfall combined with preceding periods of desiccation and cracking are expected to lead to an increase in incidents of slope failure within the transport network. A number of studies have highlighted the potential for wetting-drying and freeze-thaw cycles to induce deterioration of the mechanical and hydraulic properties of engineered fill forming infrastructure slopes with more extreme weather expected to increase the rate of these deterioration processes. The publications reviewed suggest that these deterioration processes are not yet fully understood. Bergamo *et al.* (2016) assessed the potential of surface wave data to portray the climate-related variations in mechanical properties of a clay-filled railway embankment.

Railway cuttings have been identified as a major source of risk, with several high-impact examples of failure. In 2020 in Stonehaven (Scotland), following a severe rainfall event, a passenger train hit a landslide and derailed, causing three fatalities. The Harbury landslide (2015) is cited as one of the most recent examples of cutting and embankment slips triggered by localized extreme weather events. During this landslide, 350,000 tonnes of material slipped along a 160 m long stretch leading to the closure of the stretch of line between Banbury and Leamington Spa for several weeks.

Winter *et al* (2016) assessed the economic impact of a number of debris flow events on the road network of Scotland. The study considered direct economic impacts (including emergency response and remedial works), direct consequential economic impacts (costs associated with loss of utility of infrastructure) and indirect consequential economic impacts (loss in business confidence associated with unreliable transport links). Direct costs were found to range between £400k and £1,700k, with direct consequential costs between £180k and £1,400k for the five case studies assessed.

More extreme weather conditions have triggered slope failures across the UK, especially during the extreme events of 2012. Field observations, centrifuge model testing and numerical models are methods to measure or simulate embankment behaviour; all can be supported by laboratory testing and an understanding of soil behaviour. For example, in County Down (Northern Ireland) hydrogeological processes caused unexpected instability and quick conditions during the excavation of a 25 m-deep cutting through a drumlin (Hughes *et al.*, 2016). Rouaina *et al.* (2020) demonstrated that a higher total magnitude of annual variation in pore pressures (as caused by future climate scenarios, for example) can have a significant effect on deformations in cuttings, leading to increased rates of deterioration and reduced time to failure.

Highway embankment failures induced by pore water pressure is increasing, while some railway embankments are susceptible to pore water pressure increase, seasonal shrink-swell deformation and progressive failure due to the age and nature of the dumped clay fill used in their construction (Briggs *et al.*, 2017). There is a lower risk of serviceability failure due to the shrink-swell movement of highway embankments, low plasticity fill embankments or grass covered embankments.

The effect of trees on risk due to slope and embankment failure is the subject of ongoing research. Simulations and field measurements show that while trees cause significant seasonal variations in pore water pressure and water content near the soil surface, they can maintain persistent soil suctions at depth within the tree rooting zone (Smethurst *et al.*, 2015). Leaving the trees in place over the bottom third of the slope can maintain persistent suctions at the slope toe.

Upland areas are more prone to natural slope failures due to their topography, in fact most of the studies are focused on Scotland. Similarly, mountainous areas are more prone to landslides. Regarding exposure and vulnerability, a high concentration of road/rail links or particular characteristics (e.g. high-speed rail) usually results in being more vulnerable to damage. Removal of trees in order to prevent falling branches and disruption to signals is likely to increase the landslides risk. No study has looked at slope and embankment failures comparing urban and rural context, however urban environments are more prone to flash flooding due to the high percentage of impermeable surfaces, which could cause subsidence due to run off (as in the high profile railway derailment in Stonehaven, 2020).

Landslides on coal tips are a known hazard in Wales. A major slope failure occurred at Llanwonno tip near Tylorstown in South Wales after heavy rain during Storm Dennis in February 2020. A number of minor landslips also occurred at other tips in South Wales. There are over 2,000 coal tips in Wales, predominately in the South Wales Valleys; 294 have been identified as high risk (Fairclough, 2021). With annual mean rainfall having increased in Wales, especially in South Wales (Chapter 1: Slingo, 2021), we suggest that it is possible that climate change may have already increased the risk of future slope failures.

#### 4.6.1.2. Future risk (15)

Modelling suggests that soil moisture fluctuations will lead to increased risk of shrink-swell related failures. This will be most acute in the high plasticity soils of SE England and likely to be the most significant geohazard to UK infrastructure. Wilks *et al.* (2015) considered rising temperatures (drier summers) and increasing precipitation (wetter winters) leading to slope failures along transport infrastructure within the UK. A series of slope failure case studies were investigated under 18 Weather Event Sequences (WESQs) using possible weather patterns for 2050 using UKCP09 climate projections with the high emission scenario. Although this scenario warms faster than the pathway to 4°C global warming by 2100 (see Chapter 2: Watkiss and Betts, 2020), the projected increases in heavy precipitation were smaller for a given level of global warming than in the updated projections in UKCP18 (Johns *et al.*, 2021), and hence we consider this to still be an appropriate guide to this risk in the 2050s. Each of the 18 WESQs shows a year of possible weather for the year 2050 and covers the extremes of warmest, coldest, driest and wettest. A suite of thresholds was developed based upon case studies; the 20 case studies were not of sufficient number to draw a statistically significant conclusion, but rather they illustrate trends and give a first indication as to future slope behaviour. Vegetation management for warmer trends was mentioned as potential adaptation. Wetter climates are said to produce more landslides; autumn is the most likely month for landslides for the warm and wet scenario weather, while winter for the cold and dry scenario weather. For the cold and wet scenario both autumn and winter are likely times of failure, but landslides can also occur in the summer under storm conditions.



As well as meteorological extremes, slope condition is also mentioned as a key determinant of risk. Smethurst *et al.* (2017) stated that climate change presents an increased risk to slopes. It is argued that extreme periods of climate, coupled with ageing assets, may cause a higher rate of failure. Examples of this are extreme rainfall events (both heavy showers and long periods of rain), drought and increased freeze–thaw cycles. The main driver for slope failure is rainfall, and it is possible that a hotter future European climate will see rainfall arrive in more intense storm events. Drier summers may also pose difficulties for earthworks, causing cracking and shrinkage problems in clay soils. In Europe, new road and rail systems often operate at higher speed, and the hazard posed by running into slipped debris (causing derailment or crash) is greater. Moreover, new rail and road infrastructure often rely on large amounts of earthworks, which can be impacted from increased precipitation or drought, causing increased costs and delays; this potential impact constitutes an important risk during the construction phase. A greater use of instrumentation to monitor slope behaviour may help to manage the risk that climate change poses; proactive management of slopes can be much more cost effective than reactive repairs following failure.

The sequencing of weather conditions (see Chapter 1: Slingo, 2021) is also a key factor. Dixon *et al.* (2019) underlined that cyclic seasonal effects could be potentially influenced by a changing climate. Dry summer periods remove water, leading to shrinkage and cracking; prolonged and intense rainfall events cause swelling and increased porewater pressures. Repeated shrink–swell cycles can lead to accumulation of shear strains resulting in strain softening and progressive failure.

Although Briggs *et al.* (2017) found that highway embankment failures induced by pore water pressure is increasing, the simulations undertaken in this study may not be fully representative of future embankment deterioration or the dominant physical processes influencing pore water pressures in a changing climate (e.g. surface desiccation). Tang *et al.* (2018) noted that increased precipitation, temperature and evapotranspiration (non-specified emission scenarios, based on European Environment Agency data) are likely to characterise the northwest part of Europe, and thus the UK. They highlighted risk from increased surface erosion, desiccation cracking, saturation-induced failure and shrink-swell to the stability of infrastructure slopes.

Martinovic *et al.* (2016) showed post-processed findings from an airborne LiDAR survey of the entire Irish Rail network. Slope vulnerability to shallow planar type failures is expected to increase with predicted changes in climate such as increased environmental loading (rainfall events are predicted to be more intense and of longer duration, with longer dry periods in between). This study may also have some relevance to the rail network of Northern Ireland.

Regarding canal embankments and inland waterways, projected increase in winter precipitation may increase the frequency of high flow, flooding and ‘strong stream’ conditions whereas the additional evapotranspiration associated with higher air temperatures could lead to drying out and fissuring of clay embankments and other earth structures (Brooke, 2015). Reduced waterway channel freeboard and associated lack of operating headroom could similarly compromise safety of navigation. High water levels and flood flows can threaten the integrity of navigation infrastructure through seepage, overflow or erosion and the capacity of culverts, weirs and sluices might be reduced. Extreme events are also likely to exacerbate flash floods or debris flow events involving

erosion due to atypical magnitude of surface water, as opposed to conventional deeper-seated slips within the soil.

#### 4.6.1.3 Lock-in and thresholds (I5)

Whilst minimal lock-in risks exist for known landslide sites (with engineering design codes for embankments), future climate change will increase landslide risks. There is therefore a risk of lock-in if future risks are not considered given the long lifetime and changes in land-use (with road or rails). Heavy rainfall is usually associated with a very high number of recorded landslides, thus hydrogeological triggering is seen as a main driver for slope instability. A large proportion of failures occurred on man-made slopes (embankment or cuttings), usually triggered by heavy rainfall that happens within a short time of prolonged rainfall. Pennington and Harrison (2013) developed a 'winter' threshold envelope to consider the antecedent period, water content, soil moisture and average rainfall for slope failure for SW England and S Wales. TRL (Winter *et al.*, 2019) has advanced preliminary rainfall duration-intensity thresholds based on 16 debris flow events in Scotland; these values are awaiting further validation. Briggs *et al.* (2019) developed performance curves showing the factors influencing the ultimate limit failure of embankments due to seasonal weather cycles. A key issue is the degree to which these thresholds might be exceeded under future climate change; the new UCKP18 projections indicate higher heavy rainfall projections (see Chapter 1: Slingo, 2021) than previously estimated, and these are likely to be much more evident with 4°C global warming.

#### 4.6.1.4 Cross-cutting risks and inter-dependencies (I5)

The CCRA3 interacting risks project (WSP, 2020) identified the impacts which have the greatest number of downstream connections (i.e. have the greatest potential for cascading failures throughout the infrastructure system and wider economy). Transport infrastructure damage is in the top 20 impacts with 3 connections. The project assessed the indirect impact of cascades from slope and embankment failures due to increased winter rainfall to be significant and lead to transport damage and subsequent travel delays. The level of risk of this interaction was assessed as being medium (based on impact and likelihood) in 2020 but increasing to high in 2080 (Table 4.2 in section 4.2.1).

##### 4.6.1.4.5 Implications of Net Zero

Other than increased vegetation which has the potential to improve slope stability, no specific impact of Net Zero targets on risks to transport networks from slope and embankment failure could be found, although it is reasonable to assume that rail will play a greater role in a Net Zero world, hence increasing the exposure to this element of the risk.

##### 4.6.1.4.6 Inequalities

There are implications here for the more rural areas of the UK where there is inherently less resilience in transport systems due to less dense infrastructure (i.e. single train lines). This is especially relevant where linear transport infrastructure frequently follows natural features such as steep sided river valleys prone to landslide risk. On the contrary, urban areas of deprivation are

often located close to rail lines and major roads, so their increased use could disproportionately affect these residents.

#### 4.6.1.4.7 Magnitude Scores (I5)

**Table 4.21** Magnitude scores for risks to transport networks from slope and embankment failure

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Medium	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Medium	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Medium	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

The UK has tens of thousands of km of engineered cuttings and embankments supporting its transport infrastructure. The Stonehaven incident in 2020, which led to three fatalities, and Harbury in 2015 highlight the disruption and human cost caused by rainfall induced landslides on transport infrastructure. Single landslip events in Scotland have been estimated to cause direct costs between £400k and £1,700k, with direct consequential costs between £180k and £1,400k. The length of network exposed to this risk, its vulnerability to the hazard and the observed impact of single events indicates this risk is of medium magnitude (Table 4.21). This is given with low confidence, as there is no nation-wide assessment of the economic and social consequences of slope and embankment failure on transport networks. The observation in CCRA2 that modelling shows soil moisture fluctuations will lead to increased risk of shrink-swell related failures is supported by current evidence.

## 4.6.2 The extent to which current adaptation will manage the risk (I5)

### 4.6.2.1 Effects of current adaptation policy and commitments on current and future risks (I5)

#### 4.6.2.1.1 UK wide

There is considerable investment being delivered to renew and repair rail embankments and cuttings, as part of the £2.3 billion being spent on renewing civil engineering structures between 2013/14 and 2018/19. An average of £100 million a year was to be spent on earthwork renewals during the current price control period (2014/15 to 2018/19), an increase from the average of around £75 million a year in the previous period (2009/10 to 2013/14). Expenditure on track and earthwork drainage renewals has also increased, from around £50 million a year in the previous price control period to nearer £70 million a year in the current period. Both the industry and regulator recognise that historic investment in ageing structures has been insufficient to deliver acceptable levels of risk in the long-term. There is therefore a significant backlog that will require sustained investment over the next 40-50 years to clear.

CCC (2019b) state that actions relating to rail infrastructure are associated with risk reduction, and it is likely they are reducing vulnerability in some areas, but there is not the evidence at present to quantify this. The main indicators available for rail reliability is delay data and although of interest, as an impact indicator it does not give a sense of how vulnerability or exposure to climate risk is changing. It would be useful to have a better understanding of asset, slope and embankment condition and exposure, and the standards of new adaptation interventions.

#### 4.6.2.1.2 Scotland

Specifically for Scotland, the Second Scottish Climate Change Adaptation Programme (Scottish Government, 2019b) states that Transport Scotland will be undertaking the Second Strategic Transport Projects Review (STPR2). STPR2 will identify strategic transport infrastructure interventions. The adaptation programme document also mentions the Scottish Road Network Landslides Study and Implementation Report (Transport Scotland, 2008), which takes into consideration the potential seasonal increase or decrease in rainfall and the potential impact on increased frequencies of landslides. The Integrated Roads Information System and Disruption Risk Assessment Tool has been used to record incidents including inundation and subsidence, allowing identification of vulnerable locations in the trunk road network that require engineering interventions or monitoring. More generally, the Scottish Road Network: Climate Change Study and Implementation Plan (Transport Scotland, 2008) set out recommendations to adapt the Scottish road network to cope with climate change. This used the older UKCP09 climate projections. Consideration is now being given to updating it utilising the UKCP18 projections. In terms of rail, the Scottish Ministers' High Level Output Specification, Control Period 6, sets out how investment strategies must ensure enhanced network resilience from adaptation interventions. Scottish Ministers require Network Rail to develop and apply suitable Key Performance Indicators to monitor the impact and mitigation of climate change on network disruption. This is intended to provide the means to measure the benefits of adaptation interventions.

#### 4.6.2.1.3 Wales

The Welsh Government's climate adaptation plan, *Prosperity for All: A Climate Conscious Wales* (Welsh Government, 2019b) states that Wales and West Utilities (working with Landmark Information Group) have developed an infrastructure vulnerability mapping tool (using sea level rise inundation, new tide-lines, tidal flooding, fluvial flooding for different emission scenarios and probabilities). This includes potential bridge impacts and transport infrastructure impact. There is no reference to landslips in the Future Wales: National Plan 2040 (Welsh Government, 2021a). This is Wales' new national plan, setting the direction for development in Wales to 2040, addressing key national priorities through the planning system, encompassing climate resilience.

In March 2020, the Coal Authority and the Office of the Secretary of State for Wales announced an emergency review of all coal tips in Wales (Coal Authority, 2020), categorising tips according to both their level of inherent risk and also whether the location poses a risk to people or critical infrastructure, or a risk to the environment such as rivers or other infrastructure, or are situated in a remote area (Coal Authority, 2020). This follows calls for more monitoring of coal tips following the major slope failure at Tylorstown in South Wales after heavy rain during Storm Dennis in February 2020, along with a number of minor landslips at other tips in South Wales triggered by the storm. 294 coal tips have been identified as high risk (Fairclough, 2021). The Welsh Government statement on coal tip safety (Welsh Government, 2021b) highlights the difficulties in reducing the risk of slope failures. Substantial shortcomings in current legislation and the fiscal framework regarding tip inspections and remediation have been identified. Regular inspections of disused tips is not currently mandated.

Welsh Local Authorities are responsible for 32,000km of roads in Wales. This amounts to 95% of the total road network as the Welsh Government is responsible for the Trunk and Motorway Network. Local authorities work with transport operators – bus and rail, the construction sector, planning, utilities and transport groups. The Welsh Local Government Association (WLGA) works on behalf of the 22 authorities on policy and investment in Wales' roads. A State of Wales Roads Report (Welsh Local Government Association, 2018) was published by WLGA, this did not reference the potential impact of climate change on slope and embankment failure.

#### 4.6.2.1.4 Northern Ireland

In Northern Ireland, Translink have committed to a continued geotechnical inspection regime for road and rail embankments and to prioritise actions (DAERA, 2019). Translink have been upgrading the management and infrastructure of their sites in order to adapt to climate change, including culverts on the Coleraine to Londonderry line and on the Larne line which have been sized to the latest design requirements for expected flow. A project was completed in County Antrim to replace three bridges and strengthen embankments on both the Dublin line and the Antrim Branch line. This was a scheme that was completed to ensure the area was future proofed for climate change predictions and was done as part of the improvements in that area for flood management by DfI Rivers and Coca Cola, who operate a nearby bottling plant. There is also an ongoing programme of repairs to structures and repairs following storm damage which includes activities such as rock armouring, masonry repairs, etc.

Other asset management initiatives include ongoing maintenance of 28 ‘hotspot’ areas on the rail network. These are areas of potential flooding that are managed prior to, during and after heavy rainfall. Risk analysis has also been carried out on cuttings and embankments using available DfI Rivers flooding information and we follow the weather forecasts and manage these assets during heavy rainfall periods with additional inspections, reducing train speeds, etc.

#### 4.6.2.2 Effects of non-government adaptation (I5)

Programmes have been developed to determine the amount of investment and volume of renewals required. For example, Network Rail has developed the Weather Resilience and Climate Change (WRCCA) programme which includes (i) an enhanced vegetation management strategy to mitigate the impact of extreme winds; (ii) forensic investigation of earthworks failures; (iii) earthworks remote condition monitoring pilot; (iv) improvement of drainage management; (v) agreed thresholds (e.g. water/wind levels for alert) and definitions; and (vi) an enhanced Future Weather Service for user defined geographic areas across (Network Rail, 2015). Highways England have embedded a culture of climate change adaptation planning across its assets by giving ownership of the adaptation plans to the areas of their operations at risk from climate change (Highways England, 2017), especially the increase in precipitation and temperature. These plans cover (i) drainage and pavement improvement, e.g. for overflow or thermal damage; (ii) structure and geotechnics work, e.g. earth pressure design; and (iii) sign, signal and road marking improvement for better communication.

In response to the tragic derailment at Stonehaven in 2020, which was thought to have been caused by a landslide, Network Rail launched two taskforces to look at how to prevent future impacts, as part of its long-term response to climate change and the challenge of maintaining its massive portfolio of earthworks (embankments and cuttings), many of which date from the Victorian era. The findings from the taskforces are pending at the time of writing.

#### 4.6.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I5)

As with risk I4, there have been positive developments in all UK nations to improve understanding of the risks to transport networks from slope and embankment failure, however more work is still needed to understand the extent of assets at risk, and positive action of reducing the risk. This indicates that the risk is being partially managed and that actions are reducing vulnerability in some areas. However, as there is no quantified evidence base assessing the effects of future adaptation in managing the risk, this assessment must be given with low confidence.

#### 4.6.2.4 Adaptation scores (I5)

<b>Table 4.22 Adaptation scores for risks to transport networks from slope and embankment failure</b>			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

### 4.6.3 Benefits of further adaptation action in the next five years (I5)

CCRA2 stated that further action was required to ensure that projected increases in heavy rainfall events are factored into long-term renewal programmes for earthworks, especially for the rail network. This will reduce vulnerability now and is likely to be cost-effective to implement, given that the risk is increasing with further asset deterioration combining with heavier and more frequent rainfall events.

Adaptation methods suggested within the current literature focus on providing improved numerical tools for infrastructure asset owners to predict failure occurrence, improved instrumentation and monitoring systems to detect pre-failure slope behaviour linked to decision support systems, more detailed characterisation of engineered soil assets, continued use of slope inspection programs, and greater use of soft engineering techniques such as vegetation management to reinforce vulnerable slopes. Some deterioration methods are not fully understood, which will impact adaptation strategies. Hughes *et al.* (2016) discuss the need for continuous monitoring of pore pressures during and after construction; this is mentioned as an adaptation measure.

#### 4.6.3.1 Indicative costs and benefits of additional adaptation (I5)

There are some clear low-regret options for addressing these risks. For railways, inspection and maintenance are key activities to monitor slope and embankment failure risks in advance, at a relatively low cost (RSSB, 2016b). Currently, routes use a drainage decision support tool and data collected from drainage inspections, surveys and assessments, with drainage assets currently required to be inspected at least every five years (Haines, 2020). A low-regret option would be to increase inspection frequency (especially for higher risk areas).

Drainage is also key for the stability and resilience of earthworks. There are obvious low-regret and easily implementable options for enhanced maintenance of drainage systems for addressing surface and groundwater water away from roads and railways. The costs of increasing drainage capacity in new road infrastructure also appears to be low regret, adding only a small percentage to the overall construction costs. For new builds, there are also options for improving monitoring around complex systems such as embankments; Tang *et al.* (2018) recommend remote sensing tools and report that new engineered slopes are an opportunity to design intelligent monitoring systems in a cost-efficient way, e.g. by installing systems during construction rather than retrofitting them later.

There is mixed evidence about the effectiveness of specific interventions such as vegetation management. This can help manage soil moisture fluctuations in the near-surface zone (Tang *et al.* 2018), and there is evidence that mature trees have positive effects on embankment slopes (Smethurst *et al.*, 2015). However, Network Rail reported that the removal of trees is not necessarily the cause of landslips; during summer they may cause the earthworks to dry out, and they can pose additional risks during windstorms. On the contrary, there is an increased incidence of trains running into fallen trees; vegetation management has a role to play in mitigating climate risk of earthworks, but it needs trade-off between benefits and risks (e.g. at the toe of an embankment).

Network Rail spent approximately £100 million on earthworks and drainage investment per annum

(on average) from 2009 to 2014 and was planning to double this in the subsequent five years. The benefits of these investments are in terms of avoided damage, which are very large for rail slope and embankment failure. Similar considerations are made for highways, where the costs of planned maintenance work are weighed against the risks of highway closure and repair and travel time delays. However, there is high heterogeneity with site and location (Glendinning *et al*, 2014) which means adaptation is context specific (and thus so are benefits and costs).

#### 4.6.3.2 Overall urgency scores (I5)

As discussed above, there have been positive developments in all UK nations with considerable investment being delivered to renew and repair rail embankments and cuttings. The formation of taskforces to specifically report on improved ways to manage the rail earthworks portfolio could be instrumental in the future management of this risk. There is also evidence that the latest UKCP18 projections will be utilised in adaptation work. However, as with the previous risk I4, there is presently limited evidence on the extent to which current and announced adaptation will manage the risk (although this could change pending the findings of the Network Rail taskforces), 'more action needed' scores have been assigned to each of the four UK countries (with low confidence). This action should concentrate on systematically assessing and quantifying the extent to which current plans will reduce risk to a low magnitude across the CCRA range of future climate scenarios (2°C and 4°C global warming by the end of the century, and across the 10<sup>th</sup> to 90<sup>th</sup> percentile uncertainty range within each scenario) or whether more action is needed to achieve this.

**Table 4.23** Urgency scores for risks to transport networks from slope and embankment failure

Country	England	Northern Ireland	Scotland	Wales
<b>Urgency score</b>	More Action Needed	More Action Needed	More Action Needed	More Action Needed
<b>Confidence</b>	Low confidence	Low confidence	Low confidence	Low confidence

#### 4.6.4 Looking ahead (I5)

Improved instrumentation and monitoring systems will help in the understanding of slope failure processes in relation to meteorological conditions. Work on the characterisation of engineered soil assets will assist with understanding of the spatial distribution of risk. There would be clear benefits of infrastructure owners to identify or value particular assets, such as slopes at optimal angles and direction, as natural capital, and possibly in some cases optimal for renewables generation (e.g. PVs or other renewables).



## 4.7. Risks to hydroelectric generation from low or high river flows (I6)

Hydroelectric power is vulnerable to both low river flows and extremely high river flows, however it may also benefit from increased output under more moderate increases in river flow. CCRA2 did not report a magnitude for current risk for hydropower (unknown magnitude/unknown impact). In this assessment, current risk levels are deemed to be medium (low confidence) based on the magnitude of the loss of revenue (tens of millions) caused by a reduction in generation in part due to reduced rainfall in 2018.

The future level of risk magnitude has been evaluated as medium. There is limited evidence assessing these risks, however the evidence that is available points to mixed impacts of climate change on hydroelectric generation, with generation potentially increasing in the winter and decreasing in the summer under scenarios of 2°C global warming by 2100. No studies were found which quantified the UK effects for the late 21<sup>st</sup> Century in a 4°C global warming scenario. While increased rainfall may again increase the potential for generation, there is also the possibility that more extreme rainfall events generate flow rates which are too fast to be exploited and lead to a risk of equipment damage, as well as damage downstream of hydro schemes. No research has been found on the likelihood of future physical damage to infrastructure in high flows, although it is known to be vulnerable to extreme high flows. Given future climate projections indicate more frequent, drier summers, the magnitude of risks to summer generation of hydro schemes is likely to remain medium, given it is medium under the current climate. The magnitude of risk associated with extreme rainfall events which could lead to equipment damage and consequences downstream is unknown, as these have not been included in the studies reviewed here. Further investigation would be needed to assess this risk.

Adaptation measures would include considering future river flows and incorporating climate impacts into the design of new schemes together with risk assessments for existing infrastructure and appropriate action.

### 4.7.1 Current and future level of risk (I6)

#### 4.7.1.1. Current risks (I6)

##### 4.7.1.1.1. UK-wide

Hydropower provided 2% (5,935GWh) of net electricity supplied in the UK in 2019 (BEIS, 2020b). There is currently 1875 MW (2% UK) installed capacity of natural flow (either run-of-river or impoundment) hydro power in the UK (BEIS, 2020b). The majority of existing installations, including all large (>20MW) plant, are in rural, often upland areas, however there are some smaller schemes within urban areas such as Longbridge Weir Hydro on the River Derwent in Derby. The majority of large installations are in the Scottish Highlands and North and Mid-Wales, with some in the North of England and none in Northern Ireland (UK Government, 2019; BEIS, 2019 page 99).

Hydroelectric power is vulnerable to climate impacts which lead to lower or extremely high rainfall

in the catchment area of the river or reservoir / impoundment and the resulting flow, but may also benefit from higher flows. A reduction in river flow will reduce the output of hydro power, whereas an increase in flow can increase output, up to the maximum rate for which the turbine has been designed. The impact of lower or higher rainfall on flows is mediated by the surrounding catchment area, and the consequent rate at which water reaches the river or reservoir/impoundment. Energy generation from hydro schemes is closely linked to changes in runoff (Sample *et al.*, 2015). Extreme high flows can damage or wash away generation equipment and associated infrastructure and flood the turbine house (Solaun and Cerda, 2019). Duncan *et al.* (2010) also highlight the need to assess the potential impacts of severe flood events on existing designs of spillways and weirs.

CCRA2 did not report a magnitude for current risk for hydropower (unknown magnitude/unknown impact). Since then, a reduction in all hydro generation of 7% (500GWh) in 2018 compared to 2017 was in part attributed to lower rainfall (BEIS, 2019) this includes an 11% reduction for large natural flow schemes in 2018 compared to the average output between 2014-2019 and approximately 0.2% of total power generation in 2018 (BEIS, 2020b, Tables 6.4 and 5.1.2). The magnitude of revenue from electricity associated with this reduction in output is in the order of £10s of millions. A reduction in generation of 500GWh would equate to approx. £29m of lost revenue using average 2018 prices for baseload contracts (Ofgem, 2020b). While the reduction in rainfall in 2018 has not been attributed to climate change and fluctuations in output are to be expected, the figures give an indication of the magnitude of financial losses that can be incurred from just a 7% drop in output. However, it is the pattern of output over a period of years, and its correlation with climate change, that are necessary to identify an impact. There is insufficient evidence to demonstrate that climate change is currently having an impact on hydropower. Therefore, the current magnitude is deemed low for England, Wales and Scotland and low for Northern Ireland.

#### 4.7.1.2. Future risks (I6)

##### 4.7.1.2.1. UK-wide

Future risks to UK hydropower depend on both the climate and the future of hydro capacity. Estimates suggest the potential for the development of further hydropower of 120-185MW in England and 27-63 MW in Wales (BHA and IT Power 2010); a further 400-500MW in Scotland (Sample *et al.* 2015) and 12MW in Northern Ireland (Redpath and Ward, 2014). However, the studies use different methods and technical and economic assumptions to assess feasibility, and some of the sites identified for development may have since been developed. Furthermore, their capacity estimates may be underestimated given Coire Glas, a pumped hydro scheme in Lochabar was granted planning permission in 2020 for up to 1,500MW. Although the potential for further large impoundment schemes is limited due to both environmental concerns and limited suitable sites, there is potential for further development of run-of-river hydroelectric schemes which have a design life of at least 25 years, though are likely to operate for far longer (Sample *et al.*, 2015; UK Government, 2019; BHA, 2020).

Turner *et al.* (2017) assessed the impacts of climate change on global hydropower for dam or impoundment-based schemes' output using projections reaching approximately 2°C and 4°C of

global warming by 2100<sup>8</sup>, but only presented UK results for 2050. The results for the UK as a whole for 2050 are an increase in electricity production of between -2.1–9.8% in the +2°C by 2100 scenario and 6.8–20.4% for the scenario on a pathway to +4°C by 2100, with the ranges arising from the use of 3 climate models with each scenario.

Tobin *et al.* (2018) assessed the total annual hydroelectric energy potentially available when all natural runoff in the UK is harnessed using stream flow projections consistent with future precipitation, temperature and humidity. Using several combinations of regional and global climate models and emissions scenarios, the range of projected changes in UK hydropower included both increases and decreases. At 2°C global warming reached in approximately the 2020s to 2050s, projected changes in hydropower ranged from approximately -1% to 5%, with a mean of 2%. For 3°C global warming reached in approximately the 2040s to 2070s, uncertainties were larger, with projected changes ranging from -4% to 5% and a mean of 0.5%. No clear conclusions on the projected sign of the change can therefore be drawn from this study.

Després and Adamovic (2020) used a different set of climate models and, for the UK and Ireland combined, projected similar ranges of changes in hydroelectric production as seen in the UK results of Tobin *et al.* (2018); the projections included both decreases and increases of a few percent, but with slightly more model consensus towards increasing production with 3°C of global warming compared to 2°C. Both Tobin *et al.* (2018) and Després and Adamovic (2020) assume all potential power from river flows are utilised and are resolved to the country scale rather than assessing individual sites and neither study assessed extreme events.

The relatively small changes of both these studies suggest the potential for opportunities for increased hydro production from higher river flows is marginal. van Vliet *et al.* (2016) estimated a 5 to 10% *reduction* in usable hydropower capacity by 2050 compared to a 1971-2000 baseline, using 5 climate models and scenarios reaching approximately 2°C and 4°C global warming at the end of the century<sup>9</sup> with both RCP2.6 and RCP8.5 concentration pathways. Overall evidence on future impacts is therefore mixed.

The impact of climate change on hydro output is very much dependent on future patterns of rainfall, temperature and humidity together with changes in the water catchment area. The studies reviewed demonstrate the differences in results from the use of both different climate scenarios and different hydrological models. Run-of-river schemes have at least a 25-year lifetime, with impoundment schemes having far longer lifetimes, so construction needs to consider future flow regimes, otherwise the installation can be locked in to sub optimal operation (BHA, 2020). Both winter increases in rainfall and summer droughts combine to have an overall effect on hydro output with the seasonal fluctuations in output affecting both operator and local network management.

One element missing from the studies reviewed is the impact of more extreme high and low flow

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<sup>8</sup> CNRM-CM3, ECHAM5/MPIOM and LMDZ4 climate models with the SRES B1 and A2 scenarios.

<sup>9</sup> Based on five CMIP5 climate models in the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP), with projections with the RCP2.6 concentration pathway approximately consistent with 2°C global warming by 2100, and the central estimate of the CMIP5 projections with the RCP8.5 concentration pathway being in the upper part of the range of the CCRA3 scenario of approximately 4°C global warming at the end of the century.

events (or a series of such events) on the infrastructure itself. Extreme events can damage both run-of-river and impoundment schemes, damage which can go on to affect communities and the wider environment downstream. Abstracting water for hydro-generation during periods of low flow are usually restricted to prevent or mitigate damage to the aquatic environment caused by low flows through abstraction licencing. Droughts/hotter weather can pose risks to the embankments of reservoirs which are part of impoundment schemes (Atkins 2013b). Both high peak flows and the combination of climate related hazards such as high peak flows coupled with increased debris in the water causing blockages are likely to exacerbate the risk of infrastructure damage. This interacts with increases in vegetation associated with climate change and afforestation schemes planned to mitigate climate change. Climate hazards can also exacerbate existing vulnerabilities of infrastructure schemes, even though the failure mechanisms do not relate to climate change (Atkins, 2013b).

CCRA2 did not score the future level of risk or opportunity (unknown magnitude/unknown confidence). The evidence presented here through climate impact projections points to a mixed impact of climate change with several studies suggesting the possibility of either increases or decreases in total output by various times in the 21<sup>st</sup> Century. The potential outcomes include an overall reduction in hydro power output of 10% by 2050 (van Vliet *et al.*, 2016). Impoundment schemes have the greatest ability to benefit from increased winter flow and to absorb the impact of decreased summer flow (although this depends on reservoir capacity). Run-of-river schemes cannot absorb the impact of reduced summer flows but can benefit from increased winter flow with turbines designed to operate efficiently under that regime. No research has been found on the likelihood of future physical damage to infrastructure in high flows or floods. By extrapolation, it is also assumed that an increase in any extreme flows associated with intense periods of rainfall would increase the risks of equipment damage, particularly if combined with debris within the water flows. The magnitude of risk associated with extreme rainfall events which could lead to equipment damage and consequences downstream is unknown.

#### 4.7.1.2.2. England (I6)

No specific studies on hydro output for England were identified.

#### 4.7.1.2.3. Northern Ireland (I6)

No specific studies for Northern Ireland were identified.

#### 4.7.1.2.4. Scotland (I6)

Duncan *et al.*, (2010) modelled the impact of climate change on flow duration curves of 6 catchment areas in Scotland using projected changes in rainfall in winter and summer in 2040-2050 on a pathway to 4°C global warming at the end of the century<sup>10</sup>. The results show an increase in rainfall and flow during January to April across all catchments modelled and a decrease in summer. While the study's chosen methodology limited the representation of peak flow, the results show a

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<sup>10</sup> UKCP09 Medium emission scenario

potentially far greater degree of change in the level of peak and higher flows compared to low flows. Duncan *et al.*, (2010) conclude that changes in peak winter flow and the return period of flood events raise questions about the suitability of existing spillways and weir designs. The authors suggest impoundment schemes could benefit from climate change, under the medium emission projection used, if they are able to increase their reservoir size or increase turbine capacity. Furthermore, benefits in increased mean flow could be realised if the turbine in place has been designed to operate efficiently under that flow regime.

Sample *et al.*, (2015) review current and future projections of hydropower resource in Scotland and summarise the current literature on climate impacts on hydropower more generally together with adaptation options. They conclude that run-of river schemes are more vulnerable to climate change compared to impoundment schemes as they do not have the storage capacity to buffer seasonal changes, and that decreases in run-off during summer could be offset by increases during winter – but only if schemes are designed to operate at higher flow levels (Sample *et al.*, 2015). They suggest that decreases in summer run-off and consequent reductions in generation potential may partially be offset by increases in potential for winter generation, but most schemes would be unable to benefit due to design limitations.

#### 4.7.1.2.5. Wales (I6)

Carless and Whitehead (2013) assessed the impacts of climate change on a hypothetical scheme in Plynlimon, Wales using average temperature and precipitation data from the UKCP09 High Emissions scenario for the 2080s for comparison with the projected power outputs associated with historic river flow and climate data for the Plynlimon Flume catchment area from 1985-2008. They conclude reduced output during summer could be compensated for by increased output in winter as long as there is sufficient installed capacity to take advantage of this – leaving annual generation unchanged. However, the pattern of increased output in winter months and decreases in summer months has ramifications for local power network management. While the UKCP09 High Emissions scenario warms faster than a pathway to 4°C global warming by 2100 (see Chapter 2: Watkiss and Betts, 2021), some aspects of extreme weather including heavy precipitation are projected to be more severe at a given level of global warming in more recent projections (Johns, 2021) and hence we expect the broad conclusion to still be applicable to that pathway.

#### 4.7.1.3 Lock-in and thresholds (I6)

If schemes do not take into account future flow regimes, they could be locked-in to sub-optimal operation or severe damage during extreme flow events. Run-of-river schemes are designed to operate within a specified range of river flows, specific to the site's characteristics. Power will not be produced outside of these ranges and damage can occur during high flow events.

#### 4.7.1.4. Cross-cutting risks and inter-dependencies (I6)

The CCRA3 Interacting Risks project (WSP, 2020) did not include risks to hydroelectric generation in the systems maps and dependency model due to hydroelectric generation being a highly localised process.

Land use changes within the catchment area of hydro schemes as well as changes in water requirements for other uses such as agriculture affect river flow (Sample *et al.*, 2015). Changes in land use could include afforestation which would both reduce the rate of run-off as well as reduce the volume through increased evapotranspiration. Afforestation forms part of current strategies to mitigate climate change, with increases in the use of land for forests in place of grassland proposed (CCC, 2018b). Conversely, future land use changes which remove vegetation within a catchment area (e.g. increased urbanisation) could increase the rate of run-off further and exacerbate peak flow.

#### 4.7.1.5 Implications of Net Zero (I6)

As electricity is decarbonised and other sectors increasingly become electrified, the provision of a reliable supply becomes ever more important to society and the economy. Large fluctuations in year to year or month to month generation from hydro schemes are likely to increase the challenges faced by local network operators in managing fluctuating renewable energy demand.

Neither the CCC's Net Zero scenarios (CCC, 2019a) nor the 6<sup>th</sup> Carbon Budget (CCC, 2020a) include growth in the installed capacity or output of hydro-electricity, however the 6<sup>th</sup> Carbon Budget does consider the use of further impoundment schemes with pumped storage to support electricity system flexibility (CCC, 2020b). Furthermore, changes in future costs and legislative incentives to decarbonise electricity – together with technology development – may change the economic viability of schemes currently thought to be feasible. Any climate impacts on pumped storage schemes that limit their ability to operate when required will restrict their ability to support grid flexibility and as a result the integration of renewable supplies with fluctuating outputs without wider system measures. Afforestation schemes could provide protective co-benefits to hydro schemes from high river flows if sited in relevant catchment areas, however they may also lead to an increase in the amount of woody debris entering the water following heavy rain or flooding.

#### 4.7.1.6 Inequalities (I6)

Although hydroelectric power is primarily located in rural upland locations of the UK, the centralised nature of the electricity grid ensures that this does not lead to inequalities.

#### 4.7.1.7 Magnitude scores (I6)

The present-day risk magnitude score for England, Scotland and Wales is judged as low due to a lack of evidence indicating an impact of climate change to date (Table 4.24). It is assessed as medium in the future for England, Scotland and Wales based on the reduction in output by 2050 projected by van Vliet *et al.* (2016) and the consequence of potential magnitude of foregone opportunities to the hydro power generators (based on the costs associated with a reduction in output in 2018). While the evidence presented is not in agreement on the overall impacts of 2°C global warming it does include a potential reduction in output of 5% by 2050 (van Vliet *et al.*, 2016) which could lead to £10's of millions of revenue losses (plus potential costs to the consumer, cf. I9). Secondly there are as yet no studies that evaluate the potential impacts of extreme high flows associated with either 2°C or 4°C global warming scenarios. The costs of replacing and repairing damaged equipment could

in principle be in the £10s of millions, which would be considered a medium magnitude. In combination, these reasons underpin the magnitude for England, Scotland and Wales for 2°C global warming by 2100 as medium with low confidence. The risk magnitude in Northern Ireland is deemed low because there are few major hydro power producers there (Table 4.24). Confidence is scored as low because existing studies provide diverging results and are largely based on older climate models and projections. In particular, there is a lack of studies that quantify the effects at 4°C global warming or capture the conditions leading to more extreme river flows.

**Table 4.24** Magnitude scores for risks to hydroelectric generation from low or high river flows

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Low  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Northern Ireland</b>	Low  (Low confidence)	Low  (Low confidence)	Low  (Low confidence)	Low  (Low confidence)	Low  (Low confidence)
<b>Scotland</b>	Low  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Wales</b>	Low  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)

## 4.7.2 The extent to which current adaptation will manage the risk (I6)

### 4.7.2.1. Effects of current adaptation policy and commitments on current and future risks (I6)

#### 4.7.2.1.1 UK-wide

Current adaptation policies differ between existing and new schemes. New schemes that are subject to current Environmental Impact Assessment Regulations require an Environmental Statement that should include an assessment of their vulnerability to climate change. Schemes that fall under these regulations include:

- New hydro-electric schemes above 0.5MW, as well as smaller schemes in a sensitive area

- deemed likely by planning authorities to lead to potentially significant impacts,
- Dams and other installations designed for the holding back or permanent storage of water, where a new or additional amount of water held back or stored exceeds 10 million cubic metres; and smaller schemes if they are deemed likely to cause significant impacts.

It is not clear, however, how often a climate vulnerability assessment is carried out, or how. Smaller schemes in general would fall out of this mechanism. In terms of licensing arrangements, schemes' influence on flood risk are considered and if the scheme is in a flood risk area advice on future flood risk allowances are provided. Future developments in licensing arrangements may incorporate climate adaptation requirements.

For existing schemes, owners may consider upgrading equipment for commercial purposes if financially feasible or in response to safety concerns. Those schemes which are part of reservoirs above defined limits (25,000m<sup>3</sup> in England and currently Scotland, 10,000m<sup>3</sup> in Wales, Northern Ireland and in future Scotland) would fall under the inspection regimes set out under the Reservoirs Act 1975 as amended for England and Wales, the Reservoirs Act 1975 Scotland and Reservoirs Act (Northern Ireland) 2015. The inspection regimes do not currently take climate change into account. The regulatory authorities for reservoirs are the Environment Agency (England), Natural Resources for Wales, Scottish Environmental Protection Agency and Department of Agriculture and Rural Development (Northern Ireland). Mechanisms to evaluate the climate risk or adapt existing hydro schemes to more extreme flows and potential associated damage have not been identified to date.

#### 4.7.2.2. Effects of non-government adaptation (I6)

Internationally, the need to make new hydro projects climate resilient is widely acknowledged and there is now a Hydropower Sector Climate Resilience Guide issued by the International Hydropower Association (IHA, 2019). This recognises the challenges of climate uncertainty, and recommends decision making under uncertainty approaches.

#### 4.7.2.3. Is the risk being managed? What are the barriers preventing adaptation to the risk? (I6)

It is not clear the extent to which appraisals of vulnerability of new hydro-electric schemes to climate change are being requested and/or how they are being carried out. While schemes in flood risk areas receive advice on this, other impacts of climate change may be missed. Mechanisms to evaluate the risks to or adapt existing hydro schemes to different flow regimes or more extreme flows and potential associated damage have not been identified to date. Therefore, future levels of risk are currently only partially managed.



## 4.7.2.4 Adaptation Scores (I6)

<b>Table 4.25</b> Adaptation scores for risks to hydroelectric generation from low or high river flows			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

## 4.7.3 Benefits of further adaptation action in the next five years (I6)

## 4.7.3.1. Additional planned adaptation that would address the adaptation shortfall (I6)

For new schemes, ensuring climate impacts are considered in both site selection and design will enable owners to maximise the system outputs under future climate and minimise risks of damage as far as it is possible to protect from high end events. As highlighted above, guidance is available to help such assessments (IHA, 2019). For existing schemes, retrospective climate risk assessments can better inform operational planning and take action, if necessary, to protect assets and the downstream environment from harm during high water flows or flooding. For both run-of-river and impoundment schemes, UKCP18 consistent projections of river flow and catchment processes would be required to assess the implications of future flow patterns on their operation and revenues, and in particular to assess the risks of damage to hydro-electric power infrastructure from extreme high flow events, together with the implications of changing temperatures and the patterns of drought and rainfall on embankment safety.

For existing reservoir or impoundment-based hydroelectric schemes, the suitability of spillways to future peak flow should be ensured, updating probable maximum flow rates to include climate change (Duncan *et al.* 2010). For existing and future run-of-river schemes assessing their suitability under future low and peak flows is necessary, adaptations could involve incorporating a weir – however there are wider ecological implications of weirs, making this option unsuitable (Duncan *et al.* 2010). To increase hydro power output from existing run-of river schemes during periods of increased winter flow, larger turbines can be installed (Sample *et al.* 2015), although Sample notes that increasing turbine size to take advantage of increased flows during winter would likely be at the expense of reducing further output during periods of low flow. For impoundment schemes to take advantage of higher winter rainfall, increases in reservoir sizes and or turbine capacity will be necessary (Duncan *et al.* 2010; Sample *et al.* 2015).

## 4.7.3.2. Indicative costs and benefits of additional adaptation (I6)

There is now considerable information on the technical adaptation options available for the hydro-electric generation sector, including sector specific guidance (IHA, 2019), albeit primarily focused on new builds. There are also many international studies that look at the costs and benefits of adaptation, for current plants and especially new build (e.g. Nassopoulos *et al.* 2012; Cervigni *et al.*, 2015; NRDI, 2016).

There are also several studies that look at the potential economic costs of changes in rainfall and river flows, and thus hydroelectric generation at the European level, which include analysis of the UK (van Vliet *et al.* 2016; Tobin *et al.*, 2017; Després and Adamovic, 2020). These studies project increases in hydro generation output with climate change, but there are large differences between studies (and projections and scenarios) including some projections of reductions in output, and differences between storage and run-of-river. Consideration of different studies reveals the considerable uncertainty involved, and thus the need for both low and no-regret options and iterative adaptive management. For new plants (although these are not a major focus for the UK, even under net zero scenarios), decision making under uncertainty is key, and has been applied (see international studies above).

For existing plants there are a set of no-regret options for high flows, notably with weather and climate services, for both extreme events and early warning but also more general reservoir operation optimisation. There are also various engineering options for additional spillways, and measures such as fusegates which can be added, which are generally considered low-regret options for addressing high flow risks. There are more structural options to address changes in flood return period and peak intensity, but these tend to be much more expensive.

The large downside risks for hydropower revenues are from low flows during periods of drought, especially for run-of-the-river plants. Most adaptation studies focus on turbine upgrades (e.g. EBRD, 2015) which are more cost-effective than larger structural changes (dam heightening, conveyance structures), although there is usually some degree of trade-off (i.e. lower optimisation but greater flexibility for flow variation). Turbine upgrades also offer some potential to take account of upside risks.

There is greater potential for including all these adaptation measures in the design and construction of new projects, and decision scaling has been quite widely applied to take account of climate risks and plan adaptation at the international level for such assessments (e.g. Ray *et al.*, 2015; Karki *et al.* 2015), and is incorporated in the IHA guidance (2019). However, there is often a careful balance of costs and benefits of adaptation, because of the upfront costs, versus the benefits in terms of future (and thus discounted) benefit streams.

#### 4.7.3.3 Overall urgency scores (I6)

<b>Table 4.26</b> Urgency scores for Risks to hydroelectric generation from low or high river flows				
	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	Further Investigation	Watching brief	Further investigation	Further investigation
<b>Confidence</b>	Low	Low	Low	Low

Due to the Medium rating of future risk and the gaps in assessing and managing the vulnerability of

new and existing hydroelectric schemes to climate change, Further investigation is required for this risk in England, Scotland and Wales. The score for Northern Ireland is 'watching brief' due to the small number of hydro schemes in Northern Ireland, if future developments were to take place their vulnerability to climate impacts would need to be considered.

#### 4.7.4 Looking ahead (I6)

Further information on the circumstances and related thresholds at which damage to hydroelectric schemes may occur is warranted, particularly for impoundment schemes. For new schemes assessments of future flow duration profiles which include climate impacts are needed to optimise their design. An understanding of how climate change may exacerbate other failure mechanisms is also necessary to inform both the design of new schemes and inspection and maintenance regimes of existing and future installations. Quantitative information would be particularly useful for decision makers.

### 4.8. Risks to subterranean and surface infrastructure from subsidence (I7)

Ground subsidence can occur due to shrinking and swelling of clay soils due to changes in soil water content and can also occur due to the collapse of pre-existing cavities in the ground (e.g. voids in soluble rocks and mine workings). Most subsidence is a result of shrinkage and swelling of high plasticity clays which are typically found in the south and east of England and notably around London. Damage to infrastructure often occurs as a direct result of interaction with vegetation and associated water content changes. This form of subsidence is regarded as the most damaging geohazard in Britain today by the British Geological Survey (BGS, 2018).

The majority of damage from subsidence occurs to residential and commercial property. However, transport and buried infrastructure is vulnerable to damage and disruption due to climate change-driven subsidence effects. Shrinkage and swelling of high plasticity earthworks disrupt rail track alignment leading to speed restrictions and disruption to service while repairs are carried out (Network Rail, 2018). Highway pavement can also be damaged, though this is considered a low risk due to more modern compaction methods being used in the construction of the highway network (Highways England, 2016). Buried electrical cables are sufficiently flexible to accommodate small movements due to shrink-swell subsidence and are usually located at depths where little movement occurs, hence these are considered to be at low to medium risk of damage (UK Power Networks, 2014). The potential for increased levels of leakages and burst frequency in water pipes due to shrink-swell damage has been identified by water supply companies (South East Water, 2015).

Where evidence is available, this indicates low current magnitude (e.g. £40m in costs due to subsidence in the period 2006–2016 (Network Rail, 2017a)), although it should be noted that quantitative evidence on costs is generally limited so this assessment is given with low confidence. Climate drivers suggest a potential increase in magnitude to medium, although no quantitative impact projections exist, therefore confidence in the risk scores is low. Insufficient evidence is

available to adequately differentiate between risks in the four countries of the UK. Although the risk of subsidence is well-understood, there is no systematic and comprehensive account of the amount of adaptation underway and how the risk is being reduced through these actions. Further investigation is needed to ascertain the extent to which current adaptation is managing risk.

#### 4.8.1 Current and future level of risk (I7)

##### 4.8.1.1. Current risk (I7)

Note: It has not been possible to split the evidence by UK country for this risk.

##### 4.8.1.1.1. UK wide

CCRA2 (Dawson *et al.*, 2016) reported that deformation of the ground has the potential to damage the foundations of buildings and other infrastructure, with shrinking and swelling of clay soils due to excessive rainfall, drought or land use changes being one of the most widespread forms. This is a particular problem in London and the East of England. It was reported that over one-third (35%) of 132-400kV subterranean electricity cables and 12% of high-pressure natural gas pipelines in England are located in areas of high susceptibility to shrink-swell subsidence. Additionally, some surface infrastructure assets are also located in areas of high susceptibility, including 10% of clean water treatment works, 15% of small (<50m) telecommunication masts and 8% of high voltage (<400kV) electricity pylons. Over one-fifth (22%) of Category 1 rail lines, 29% of major train stations and 9% of the major road network are located in high susceptibility areas. Modern compaction methods ensure that the clay fill in highway embankments have a low permeability, which together with the road surfacing and effective drainage measures, mean that rainfall infiltration into road foundation soils is relatively low and hence shrink-swell is a comparatively lower risk. However, it should be noted that roads have been observed to be subject to apparent drought-related subsidence (Pritchard *et al.*, 2014).

Soil shrinkage during dry periods followed by swelling causes disruption to track alignment and road surfaces (Tang *et al.*, 2018; Markolf *et al.*, 2019). On railway lines this leads to periods where speed restrictions must be applied and increases maintenance costs. Network Rail reported £40m in costs due to subsidence in the period 2006–2016 (Network Rail, 2017a), and whilst subsidence was not one of the most frequent climate-related events, these events were amongst the highest in terms of costs per incident.

Roadways are less vulnerable but may experience some additional damage to pavement surfaces. The magnitude of surface movement is strongly influenced by the presence of deep-rooted, high-water-demand trees (Briggs *et al.*, 2016, Kamchoom and Leung, 2018). Magnitudes of shrink-swell can also be increased by changes in near surface permeability caused by the formation of desiccation cracking in warm weather (Dixon *et al.*, 2019). Nasr *et al.* (2019) also identified a risk to bridge foundations from shrink-swell action, though did not present cases where such damage had occurred.

The formation of sinkholes under road and rail infrastructure can be caused by prolonged or

extreme rainfall. Areas underlain by soluble rocks are most vulnerable where rapid dissolution can lead to the formation of new voids which can then collapse, leading to settlement at the surface. The collapse of poorly capped and filled mineshafts can exhibit the same effects. Indeed, many areas of the UK have a rich heritage of mining which can lead to collapse or subsidence of the overlying surface. For example, there are over 2,400 known abandoned mine workings in Northern Ireland, containing vertical shafts and horizontal adits extending underground to great distances.

Buried services are located close to the surface within the zone where wetting and drying effects are at their greatest, meaning they are also exposed to the shrink-swell effects impacting transport infrastructure listed above. Shrink-swell ground movement can cause damage to pipes and cables and disruption of services particularly where these are made from rigid materials or are poorly maintained. In 2011 a prolonged period of high temperatures and dry conditions in Houston, USA, saw the number of water main breaks increase by 250%, though high water demand was also believed to have played a part (Markolf *et al.*, 2019). Studies in the Netherlands have also identified patterns of increased frequency of water pipe failure during periods of drought (Wols *et al.*, 2018).

#### 4.8.1.2. Future Risk (I7)

##### 4.8.1.2.1. UK-wide

CCRA2 reported that no data were available on future risks from subsidence. The British Geological Survey have since projected an increased risk of shrink-swell subsidence in high plasticity soils in the South East of England due to moisture content changes which has the potential to impact road and rail corridors (BGS, 2018). This study used a scenario at the upper end of the range defined as the CCRA3 pathway to 4°C global warming at the end of the century<sup>11</sup>. Asset owners have reported subsidence as a risk in climate adaptation plans. It can be assumed that railway track and road surfaces, buried pipelines of water, electricity mains and gas supplies are likely to be impacted by climate change. Ground movement/subsidence, shrinkage and heave of high plasticity soils are expected to be exacerbated by projected increases in drought conditions and periods of prolonged heavy rainfall (Tang *et al.*, 2017; Markolf *et al.*, 2019). Dixon *et al.*, (2019) demonstrated changes in seasonal permeability of a number of UK infrastructure cuttings and embankments and concluded that increased summer drying would lead to additional desiccation cracking and higher permeabilities. This in turn would lead to shrink-swell effects permeating deeper into the soil. Development of sinkholes after periods of prolonged rainfall, local flooding and erosion are also anticipated to be causes of damage.

Insufficient evidence is available to adequately differentiate between risks in the four countries of the UK. However, it has been noted that a knowledge and research gap exists around the potential impact of climate change on soils, landslips and subsidence in areas which have been mined, particularly in Wales.

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<sup>11</sup> The 50<sup>th</sup> percentile of the UKCP18 probabilistic UK projections with RCP8.5 emissions. The 50<sup>th</sup> percentile of the UKCP18 global projections reaches 4.2°C warming at 2070-2099 with RCP8.5 emissions. See Chapter 2 (Watkiss and Betts, 2021) for further details.

#### 4.8.1.3 Lock-in and thresholds (I7)

The buried and surface infrastructure exposed to subsidence risk have long operational lifetimes, so consideration of this risk for correct construction and maintenance is essential. The quality of evidence available indicates that there are presently no easily defined thresholds.

#### 4.8.1.4 Cross-cutting risks and inter-dependencies (I7)

Buried services are frequently co-located beneath or alongside transport corridors. In the context of climate change this geographic interconnectedness could result in a variety of failure modes (Markolf *et al.*, 2019). For example, extreme drought could lead to shrink-swell around a water pipe leading to fracture, in turn leading to local flooding and erosion of subsoil, potentially forming a sinkhole affecting nearby roads. Soil shrinkage during dry periods followed by swelling causes disruption to track alignment and road surfaces. On railway lines this may lead to increased periods where speed restrictions must be applied and increase maintenance costs.

The CCRA3 interacting risks project (WSP, 2020) identified the impacts which have the greatest number of downstream connections (i.e. have the greatest potential for cascading failures throughout the infrastructure system and wider economy). Impacts to earthworks and pipe movements had four downstream connections identified and are starting points for cascading risks related to transport. For example, a reduction in summer rainfall could lead to soil desiccation in the natural environment, then earthworks and pipe movement and subsequently impact transport through failures and delays. However, the project did not define these interactions as being significant in 2020 or 2080 (i.e. contributing to the overall level of risk).

#### 4.8.1.5 Implications of Net Zero (I7)

Increased tree planting (e.g. on embankments) may increase shrink-swell risk (Briggs *et al.*, 2016). It can also be expected that rail travel will be of greater importance in a Net Zero future and hence the level of disruption caused by shrinking and swelling soils under rail lines, particularly in the densely populated south-east of England, would increase with higher volumes of rail traffic.

#### 4.8.1.6 Inequalities (I7)

Damage due to shrinking and swelling related subsidence is more likely in the south and east of England and around London. Other parts of the UK are less likely to be impacted due to lower incidence of high plasticity clay soils. Void collapse related subsidence is related to the presence of soluble rocks and abandoned mine workings. Collapse of cavities created by the dissolution of soluble rocks is rare. The majority of soluble rocks in the UK occur within England. Abandoned mine workings are concentrated in the midlands, North East England, South Wales and southern Scotland.

#### 4.8.1.7 Magnitude scores (I7)

Where evidence is available, this indicates low current magnitude (e.g. £40m in costs due to subsidence in the period 2006–2016 (Network Rail, 2017a)), although it should be noted that

quantitative evidence on costs is generally limited so this assessment is given with low confidence (Table 4.27). Climate drivers suggest a potential increase in magnitude to medium, although no quantitative impact projections exist therefore confidence in the risk scores is low. Insufficient evidence is available to adequately differentiate between risks in the four countries of the UK.

**Table 4.27** Magnitude scores for risks to subterranean and surface infrastructure from subsidence

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Low  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Northern Ireland</b>	Low  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Scotland</b>	Low  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Wales</b>	Low  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)

## 4.8.2 The extent to which current adaptation will manage the risk (I7)

### 4.8.2.1. Effects of current adaptation policy and commitments on current and future risks (I7)

#### 4.8.2.1.1 UK-wide

Limited information is available to assess the extent to which current adaptation will manage this risk in the four current National Adaptation Programmes covering the UK. This might be a result of the ‘watching brief’ urgency score given to the risk across the UK in CCRA2. Some general actions are included that are relevant to managing subsidence, such as raising awareness of the risks to infrastructure networks from climate impacts.

#### 4.8.2.2 Effects of non-governmental adaptation (I7)

It was stated in CCRA2 that ‘Infrastructure operators understand this risk well and there are established processes in place to monitor the risk and manage assets accordingly’. Subsidence risks

are widely recognised in the infrastructure asset owner community. For example, this risk is handled within Network Rail's Earthworks Technical Strategy covering Great Britain (Network Rail, 2018). Furthermore, transportation infrastructure asset owners are actively engaging with academic researchers regarding geotechnical risks. Utilities companies have collaborated with the UK Geospatial commission to establish a national underground asset register (NUAR) which may prove useful in identifying utilities located in shrink-swell susceptible soils. However there remain gaps in understanding the level of the risk at the national level.

#### 4.8.2.3. Is the risk being managed? What are the barriers preventing adaptation to the risk? (I7)

Although the risk of subsidence is well-understood, there is no systematic and comprehensive account of the amount of adaptation underway and how the risk is being reduced through these actions. As there is no evidence base assessing the effects of future adaptation in managing the risk, this assessment must be given with low confidence.

#### 4.8.2.4 Adaptation Scores (I7)

<b>Table 4.28 Adaptation scores risks to subterranean and surface infrastructure from subsidence</b>			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

### 4.8.3 Benefits of further adaptation action in the next five years (I7)

#### 4.8.3.1 Additional planned adaptation that would address the adaptation shortfall (I7)

More research is needed for the production of more accurate and consistent data, for investigating the interdependencies of infrastructure and understanding potential adaptation strategies (mainly limited to monitoring at present). The heterogeneity of railway earthworks is a challenge to understanding their future behaviour. More detailed information on sub-surface composition would assist in predicting future behaviour but would be costly to achieve. Quantifying the uncertainty in soil properties would be beneficial.

Removal of trees from railway embankments has been shown to reduce shrink-swell movement, though this comes at a cost of reducing the reinforcement effect of tree roots and increases in pore water pressure leading to loss of stability (Briggs *et al.*, 2016). Increased ground and weather monitoring and the use of real-time decision support tools has been proposed as a potential method to mitigate the risks of shrink-swell.

#### 4.8.3.2 Indicative costs and benefits of additional adaptation (I7)

Land subsidence tends to be a slowly progressing threat, which can reduce the incentives for early



action (Erkens and Stouthamer, 2020). As a result, most information is on repair costs, i.e. after subsidence has occurred (especially for residential and commercial properties). As highlighted above, there are some potential risks for rail tracks (but lower risks for highway pavements) as well as potentially some risks to buried infrastructure. There are some low-regret options, e.g. increased monitoring in higher risk areas, as well as vegetation control, but there appears to be little information on the costs and benefits for future climate risks.

#### 4.8.3.3 Overall urgency scores (I7)

Further Investigation scores have been assigned to each of the four UK countries (low confidence). There is a need to concentrate on systematically assessing and quantifying the extent to which current plans will reduce risk to a low magnitude across the likely range of future climate scenarios (2–4°C, and across the 10-90<sup>th</sup> percentile uncertainty range within each scenario) or whether more action is needed to achieve this.

<b>Table 4.29 Urgency scores for risks to subterranean and surface infrastructure from subsidence</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	Further Investigation	Further Investigation	Further Investigation	Further Investigation
<b>Confidence</b>	Low	Low	Low	Low

#### 4.8.4 Looking ahead (I7)

The railway network in the South East of England is particularly exposed to this risk and the costs associated with subsidence are disproportionately high. Therefore, this is a risk that may become increasingly important as the trend towards wetter winters and hotter, drier summers continues.

### 4.9. Risks to public water supplies from reduced water availability (I8)

The UK faces an increased demand for water in a changing climate. Analysis commissioned for CCRA3, and consistent with other studies, indicates that the UK as a whole currently has a supply/demand surplus of 950 Ml/day. However, without adaptation and under a central population scenario, a deficit across the UK of between around 1220 and 2900 Ml/day (for the range between 2°C to 4°C global warming) is projected by the late 21<sup>st</sup> century, equating to the daily water usage of around 8.3 to 19.7 million people (based on the present day average per capita consumption of 140 l/h/d). Without adaptation, all water resource regions in England and parts of Wales are projected to be in deficit under a central population scenario with 4°C global warming by the late 21<sup>st</sup> century. Adaptation efforts in the sector are advancing, driven by 5-yearly Water Resource Management Plans which take an outlook of at least 25 years. These currently demonstrate a commitment to a number of ambitious targets to reduce leakage, reduce per-capita consumption and outline a range of options to improve resilience via new water supply infrastructure.

Evidence from the CCRA projections of future water availability (HR Wallingford, 2020) suggests that current and announced adaptation will manage risk in Northern Ireland, Scotland and Wales. In England, the current and announced adaptation scenario is less successful in reducing the magnitude of deficits to a low magnitude in the late 21<sup>st</sup> century. Current action should be sustained in Northern Ireland, Scotland and Wales. More action is needed in England. The Environment Agency's recent National Framework (2020c) provides direction on what this action may involve.

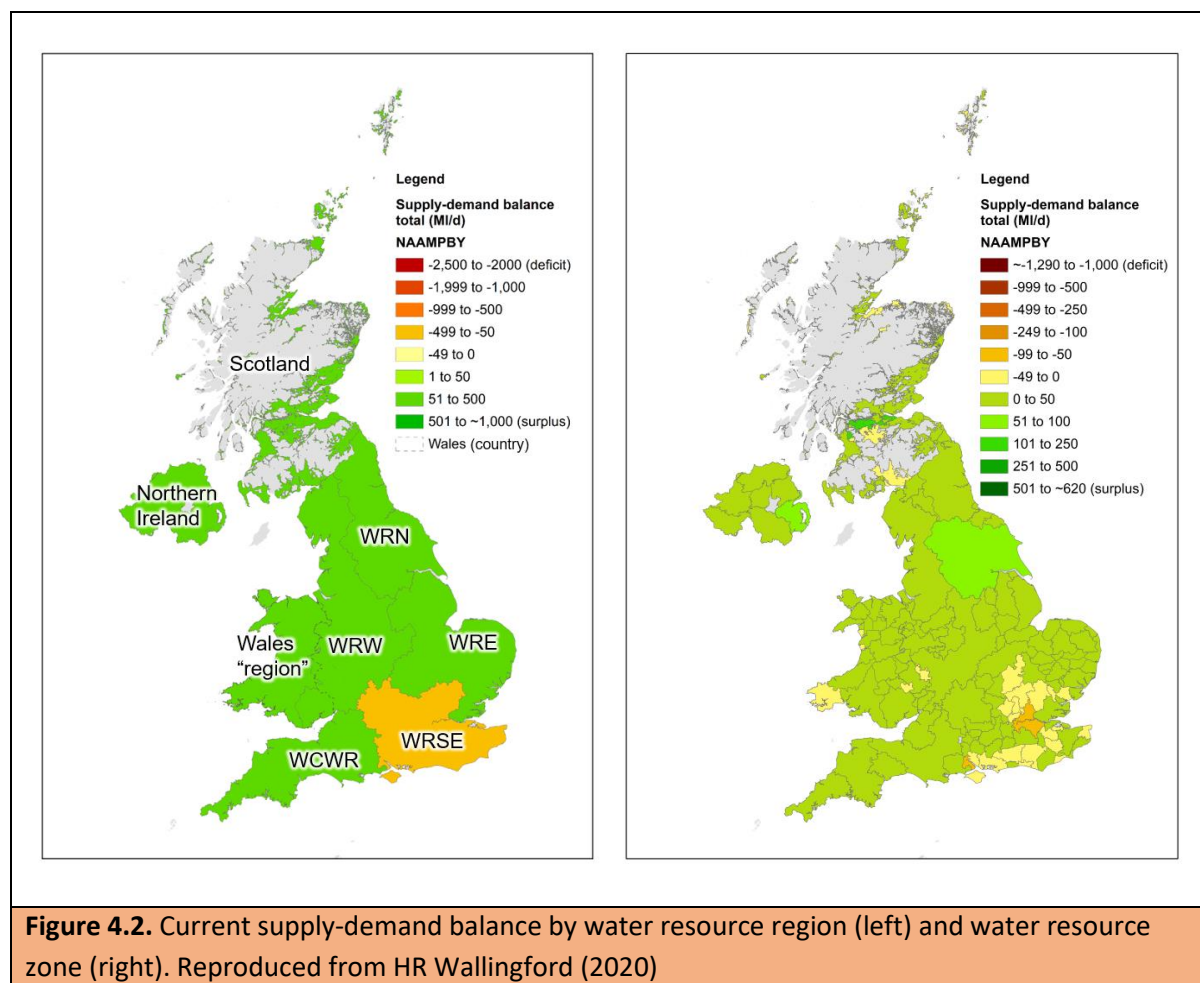
#### 4.9.1 Current and future level of risk (I8)

##### 4.9.1.1. Current risk (I8)

##### 4.9.1.1.1. UK-wide (I8)

CCRA2 (Dawson *et al.*, 2016) reported a (then current) overall supply/demand surplus of around 2,000 Ml/day across the UK. Modest deficits in water resource zones (mainly in some parts of southern England) were identified, although these deficits were all lower than the target headroom (the minimum buffer that companies should plan to maintain between supply and demand in order to cater for current and future uncertainties). These results have since been superseded by the future water availability analysis conducted for CCRA3 (HR Wallingford, 2020) which gives an overall current supply/demand surplus of around 950 Ml/day for the UK as a whole. The reduced surplus compared with CCRA2 is attributed to changes in the way water companies in England and Wales account for climate change in the 2019 Water Resource Management Plans; companies were required to incorporate climate change in Deployable Output, including an allowance for historical impacts. It should be noted that the HR Wallingford assessment of present-day risk is based on water company draft baseline plans for WRMP19, as at the time of completing the CCRA3 analysis the final plans had not been approved.

Although the vast majority of water resource zones (the standard spatial unit of water supply evaluation in England and Wales) currently operate a surplus, around 16.7 million people live in water resource zones that are nominally in deficit (7.89 million people in London) (Thames Water, 2019; HR Wallingford, 2020). This indicates that there are a minority of water resource zones where the 1 in 200-year drought resilience level of service is yet to be reached based on draft baseline plans (although it should be noted that WRMPs ensure that this level of service will be reached within the next 5-10 years). Analysis also aggregates supply-demand deficit at a regional level (South East, East, West Country, West, North, Wales, Scotland, and Northern Ireland), with the South East the only region with a present-day (nominal) deficit (HR Wallingford, 2020). However, the regionalisation assumes that water can be readily shared between water resource zones within the regions, which in reality varies in feasibility across the country (for example, in Scotland and parts of Wales this can be prohibitively expensive). Present day supply-demand balances at the regional and water resource zone levels of aggregation are given in Figure 4.2. It must be noted that regionalisation can obscure hotspots in regions that are otherwise at surplus.



HR Wallingford (2020) state that the projected present-day deficits often reflect recent sustainability reductions or climate change impacts to which companies have yet to adapt, as all water companies have to produce a positive supply-demand balance as part of their WRMPs. In reality, this means that a water company may not currently meet its specified target levels of service and drought resilience (noting that specified levels of service vary between companies). It is stated that water companies may already be attempting to obtain other sources of water through new supply schemes or transfers and/or are taking advantage of reductions in demand in other areas such as power plant closures. This suggests that some of the projected present-day deficit in the HR Wallingford (2020) projections may be the result of the discrepancy between the data used in the analysis and the data used in final water company plans. However, Thames Water (2019) identified an immediate and increasing supply-demand deficit in the London Zone, in their final WRMP (2019).

A review of recent scientific evidence for past changes in UK water availability shows that there has been no robust, formal attribution of observed changes (to date) in any component of the UK water environment to anthropogenic climate change (Garner *et al.*, 2017 – see also Chapter 1: Slingo, 2021). The review also found, however, comprehensive evidence for observed changes in precipitation and river flows.

Further complexity derives from risks to key assets in the sector. Water is often stored in reservoirs, which are vulnerable to high water flows and increased temperatures due to their implications for

bank integrity. This was previously highlighted in CCRA2 and further reinforced by the incident at Whaley Bridge earlier in 2019, (see case study, section 4.15: although not related to public water supply) which demonstrated that high levels of rainfall can be a contributing factor to spillway failure. The vulnerability of reservoirs largely depends on their construction method, which in the UK normally includes earthfill embankments and non-erodible structures such as concrete or masonry. Earth banked construction methods are vulnerable to erosion from rainfall, whereas concrete surfaces are vulnerable to conditions causing cracking or joint movement (Atkins, 2013). Overflow structures and spillways may also be vulnerable due to increasing frequency and size of flows and catchment impacts that might increase debris and vegetation. Auxiliary structures such as valves or draw off towers may be vulnerable to similar effects and can be prone to other factors such as siltation or heat induced expansion.

#### 4.9.1.2. Future risk (I8)

The updated projections of future water availability for the UK produced for CCRA3 (HR Wallingford, 2020) provide analysis for the potential impact of climate change at a number of different scales of spatial aggregation and for a variety of population and adaptation scenarios. These water availability projections for the UK are the first of their kind to use the UKCP18 Climate Projections. Population scenarios, developed by Cambridge Econometrics (2019), are used at the water resources zone, regional and country scales, flow scenarios from Future Flows and UKCP18 global projections are used, along with demand modelling developed for Water UK (Artesia). A summary of the projections is given below.

##### 4.9.1.2.1 Mid-century supply-demand balance

###### 4.9.1.2.1.1 UK-wide

HR Wallingford (2020) assessed mid-century supply-demand balance under a central population projection scenario with no additional adaptation for pathways to approximately 2°C and 4°C global warming in the late 21<sup>st</sup> Century<sup>12</sup>. These were termed “2°C world” and “4°C world” in that study. Under these assumptions the UK faces a supply-demand balance deficit of between 650 and 920 Ml/d (equating to the daily water usage of around 4.4–6.2 million people for 2°C and 4°C global warming respectively). It is projected that three of the eight regions in the UK will be in deficit by mid-century. The increase in demand from a rising population places additional pressure on water resources even when the impact of climate change is relatively low. When simulating future balances using a high population scenario, a UK-wide supply-demand balance deficit is evident. In the mid-century, population scenario is the key determinant of supply-demand balance, with the difference in impact between the low and high population projections around 3,220 Ml/d day at a

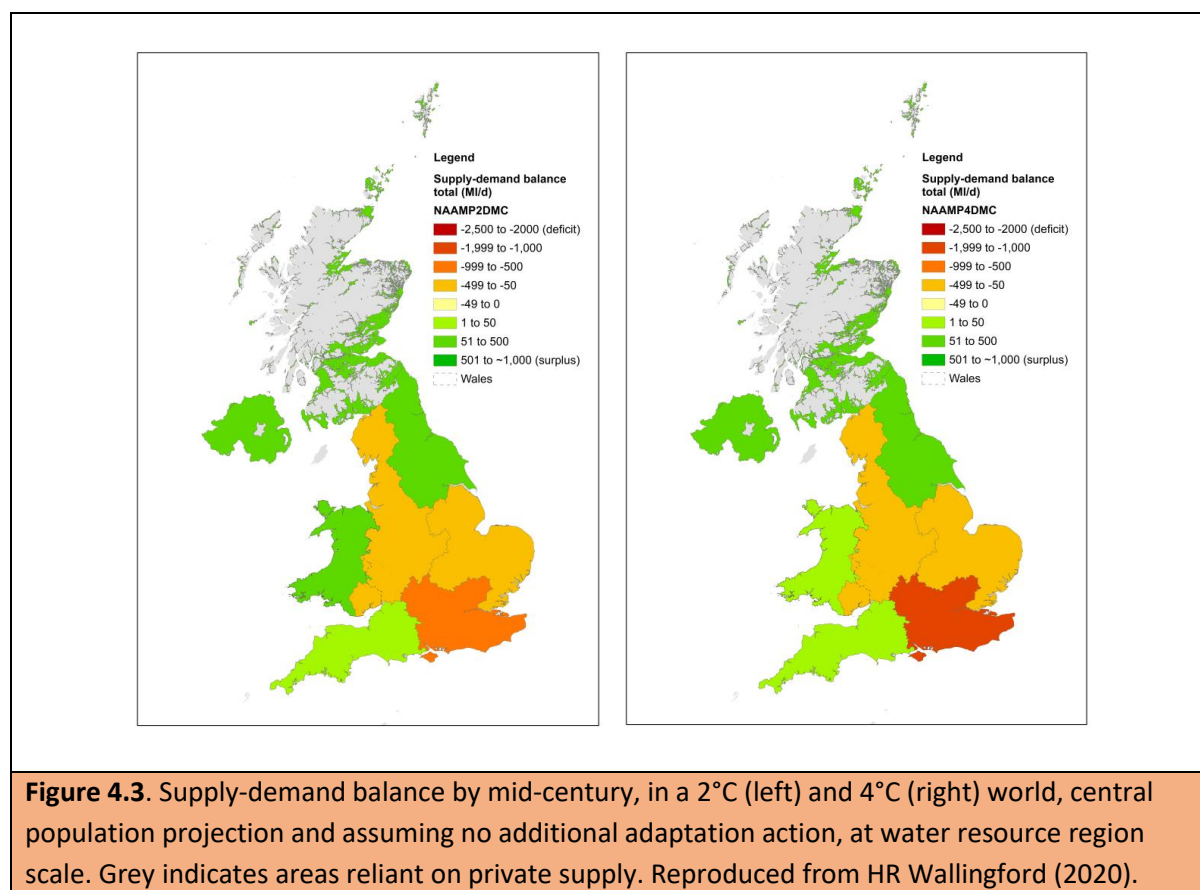
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<sup>12</sup> The HR Wallingford (2020) method defined the 2°C and 4°C pathways as the global warming levels (GWLs) reached late century (2070-2099) at the 50<sup>th</sup> percentiles of the UKCP18 probabilistic projections with the RCP2.6 and RCP8.5: 1.8°C and 4.2°C respectively. The former is near the centre of the lower CCRA3 scenario, and the latter is on the upper bound of the CCRA3 higher scenario (see Chapter 2: Watkiss and Betts, 2021). Late-century regional climate states were taken from the UKCP18 perturbed-parameter ensemble (PPE) of global 60km projections at those GWLs. Mid-century climate states were taken from the 60km PPE at the GWLs reached with RCP2.6 and RCP85 50<sup>th</sup> percentiles in 2040-2069. See HR Wallingford (2020) for details.

national scale. The projected impact of climate change on the supply-demand balance at the UK scale is around 10% of the range of the potential projected impact of population growth. However, while the difference between supply-demand balances for 2°C and 4°C worlds under the central population scenario is relatively small at 270 Ml/d, this is nearly 30% of the current supply-demand balance surplus. It should be noted that the regionalisation of results assumes that water can be readily shared between water resource zones within each region.

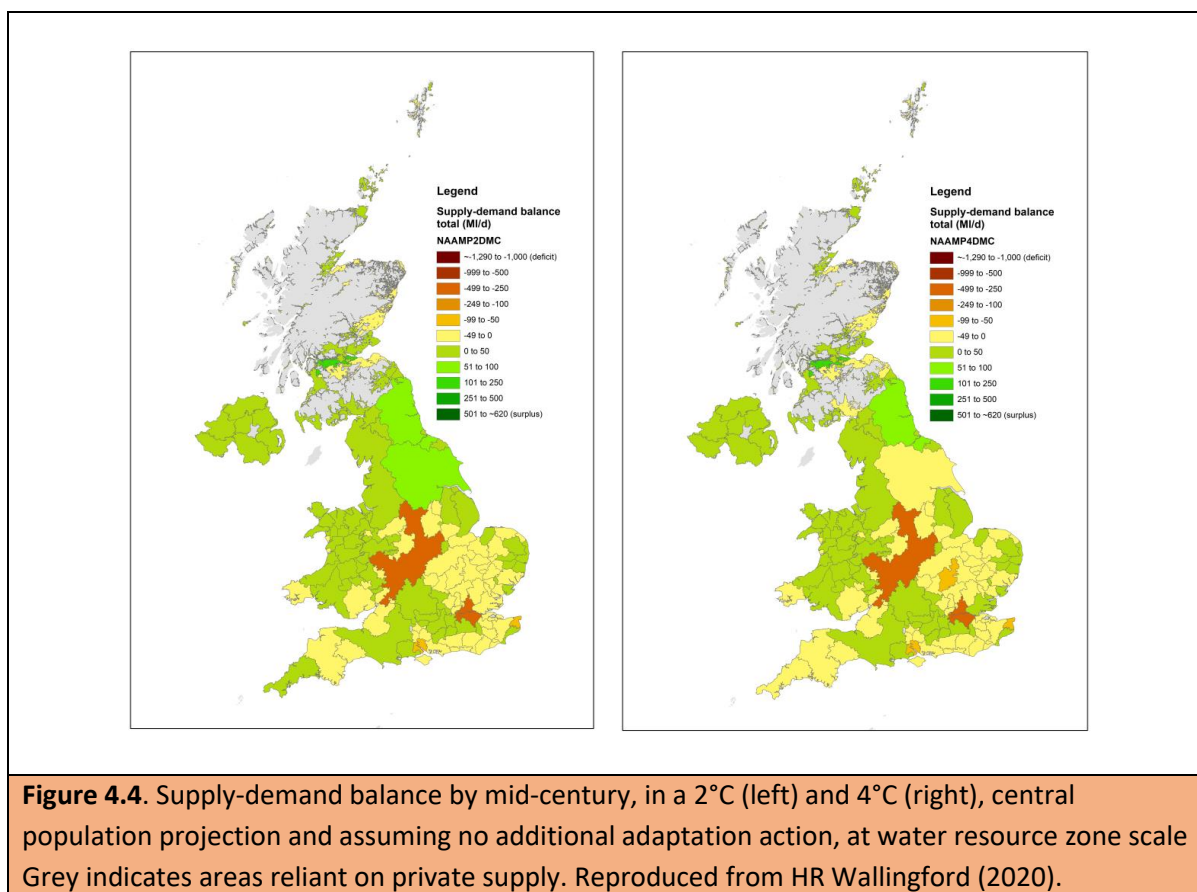
#### 4.9.1.2.1.2 England and Wales

Figure 4.3 indicates deficits in regions of England and the south east region of Wales by mid-century, in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action. Water Resources South East, Water Resources West and Water Resources East are all projected to have deficits under both scenarios. Figure 4.4 shows the supply-demand balance for the more granular water resource zone scale, which shows deficits in zones within the Wales Region, in addition to the regions of England identified above.



#### 4.9.1.2.1.3 Northern Ireland

All water resource zones in Northern Ireland remain in supply-demand surplus in the mid-21<sup>st</sup> century, in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action. Surpluses are also projected in all water resource zones (Figure 4.4).



#### 4.9.1.2.1.4 Scotland

Scotland has an overall supply-demand balance surplus by mid-century under the central population scenario and for both 2°C and 4°C worlds (Figure 4.3). However, some water resource zones in Scotland are in supply-demand deficit by the mid-century, in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action (Figure 4.4). Scotland has 191 water resource zones and large areas of the country have no public water supplies, only private ones.

#### 4.9.1.2.2. Late-century supply-demand balance

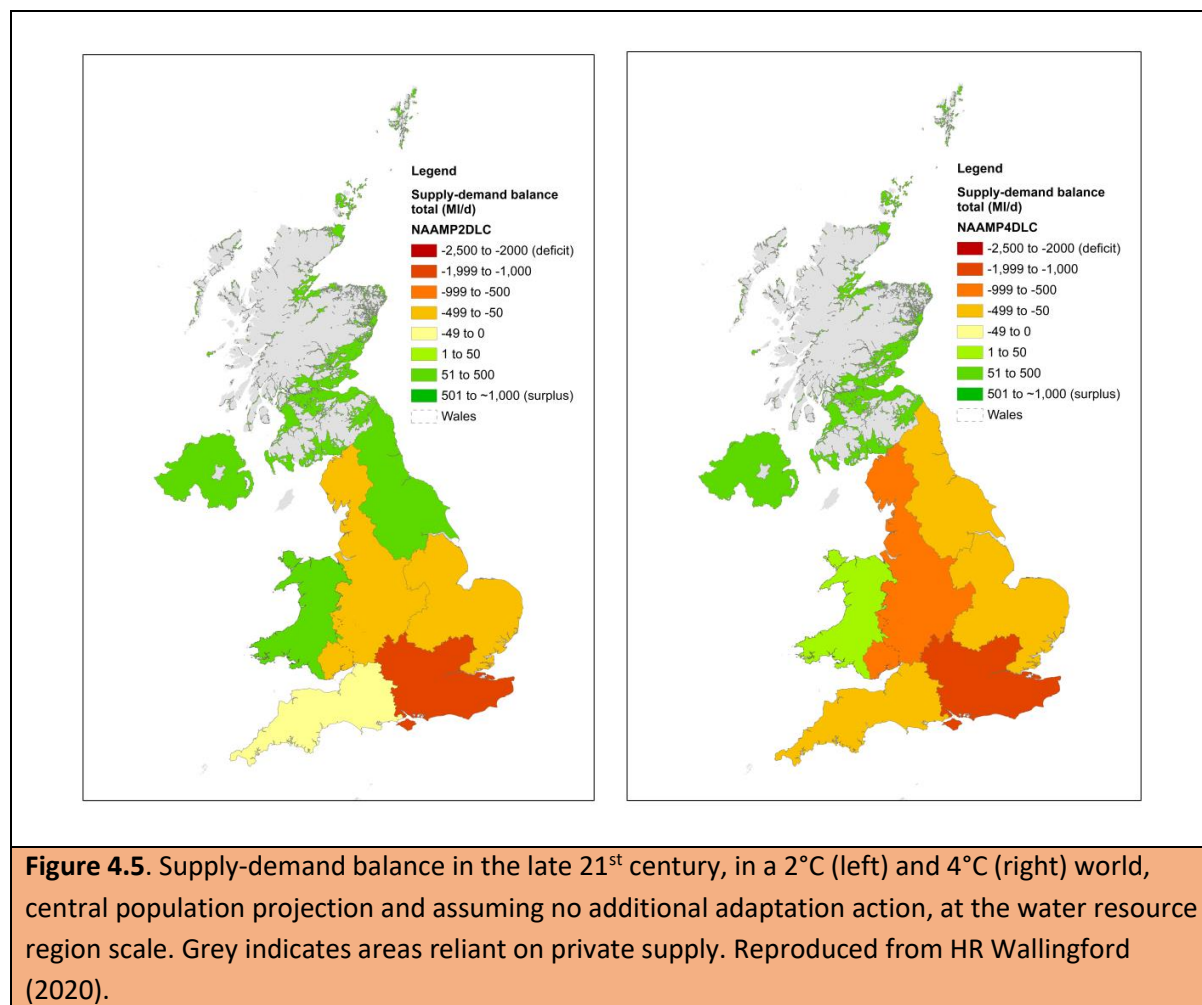
##### 4.9.1.2.2.1 UK-wide

Under a central population scenario with no additional adaptation, a deficit across the UK of between around 1220 and 2900 MI/d (2°C and 4°C worlds) is projected by the late century, equating to daily water usage of around 8.3 to 19.7 million people (based on the present day average per capita consumption of 140 l/h/d). The central population scenario is taken from the CCRA3 socio-economic scenarios developed by Cambridge Economics (2019), based on ONS 'principal projection scenario', which assumes demographic patterns in future such as fertility, mortality and migration trends remain the same as current trends. Indeed, the Environment Agency (2020c) highlights the relative importance of population change when compared to climate change with the former contributing to the deficit significantly more (notwithstanding measures to increase drought

resilience).

#### 4.9.1.2.2.2 England and Wales

Figure 4.5 indicates deficits in regions of England and the south east of Wales by the late 21<sup>st</sup> century in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action. Notably, in a 4°C world, all water resource regions in England are in deficit (as well as part of South East Wales). Figure 4.6 shows the supply-demand balance for the more granular water resource zone scale.



The NIC proposal to increase water supply resilience in England to withstand a 1 in 500-year drought has recently been accepted by the Government, meaning the next round of water company plans due in 2024 will have to plan to deliver resilience to these events. This also applies to the area of Water Resources West in Wales. This was informed by the NIC's (2018b) report on preparing for a drier future. In this, the NIC demonstrated that, at the time of analysis, a severe drought (0.5% annual probability) would result in an additional shortage of between 600 and 800 Ml/day, rising to between 800 and 1000 Ml/day for an extreme drought (0.2% annual probability). The report compared the costs of proactive, long-term resilience versus relying on emergency responses beyond current resilience levels. It was found that providing proactive, long-term resilience was cost

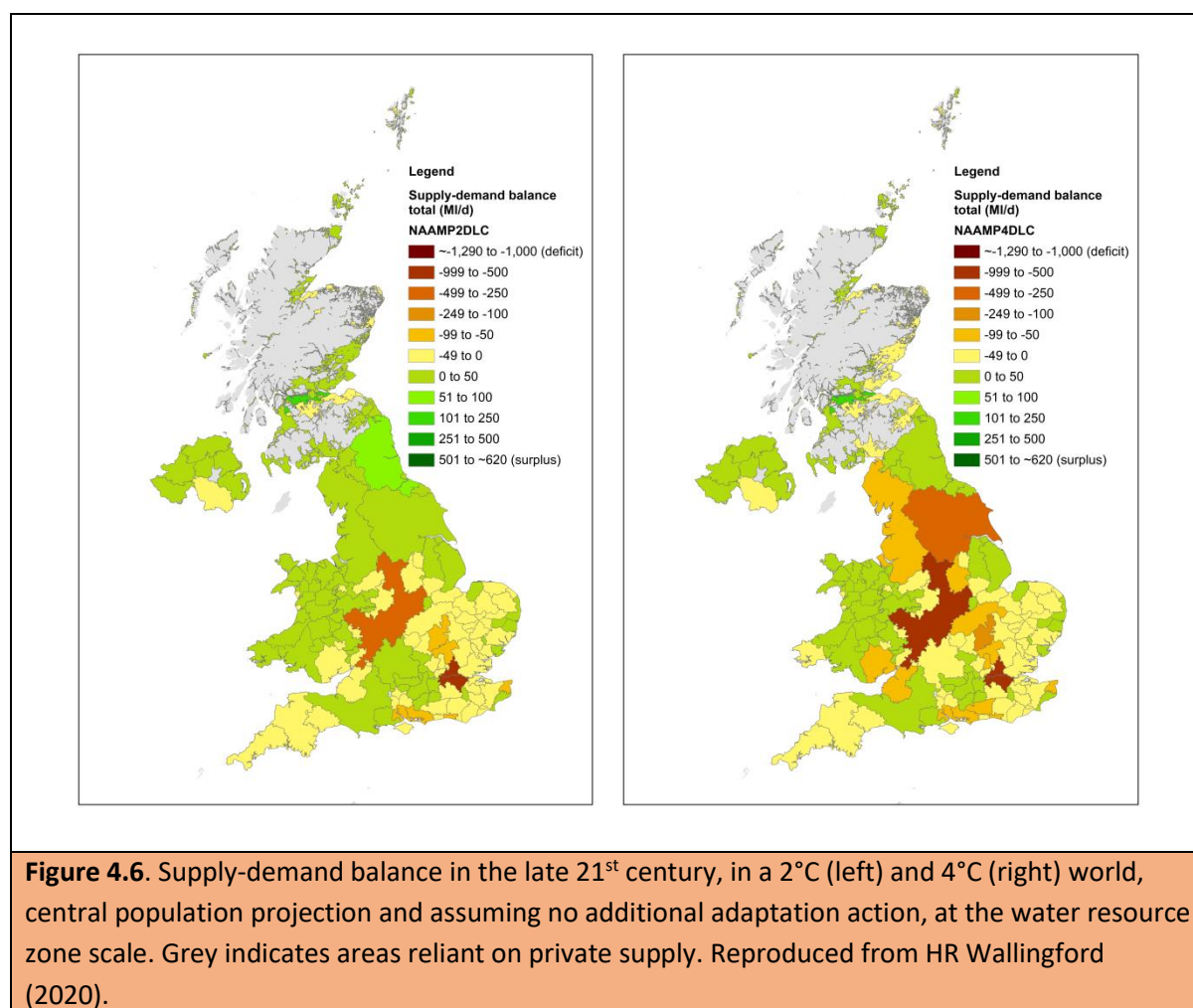


effective (costing between £18 billion and £21 billion) compared with relying on emergency responses (between £25 billion and £40 billion).

Building on previous work by Water UK (2016), the Environment Agency produced their National Framework for Water Resources (Environment Agency, 2020c). The work focuses on the regional requirements for the five regional water resources groups to meet future demand. Analysis using the WRMP19 plans demonstrate that if no action is taken between 2025 and 2050 around 3,435 MI/d) extra capacity would be needed in England by 2050, and 5,500 to 6,000 MI/d by 2100 (again, assuming no further action). It must be noted that this analysis is based on older UKCP09 projections, with water companies using a variety of approaches in their WRMPs.

#### 4.9.1.2.2.3 Northern Ireland

Northern Ireland has an overall supply-demand balance surplus by the late-century under the central population scenario and for both 2°C and 4°C worlds. One water resource zone in Northern Ireland is projected to have a supply-demand deficit in the late 21<sup>st</sup> century, in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action (Figure 4.6).





#### 4.9.1.2.2.4 Scotland

Scotland has an overall supply-demand balance surplus by late-century under the central population scenario and for both 2°C and 4°C worlds (Figure 4.5). However, Figure 4.6 shows that a number of water resource zones in Scotland will be in deficit by the late 21<sup>st</sup> century, in both 2°C and 4°C worlds under central population projection and assuming no additional adaptation action.

In a low likelihood, high impact, scenario (4°C global warming reached more rapidly than the CCRA3 higher scenario<sup>13</sup>) with high population and no additional adaptation actions, all regions of the UK are projected to be in supply-demand balance deficit by late-century.

The relative contribution of climate change to changes in public water supply is mediated by changes in water demand, land use change and water resource management (Water UK, 2016; Hutchins *et al.*, 2018). Changes in demand for water include changes in both population size and per capita consumption, economic growth and the demand profile of the future economy together with associated abstraction licences, and the success of measures to reduce leakage (Water UK, 2016). Changes in land use can alter the rate and pace of run off as well as groundwater recharge and the environmental quality of water bodies from which water can sustainably be extracted (Hall *et al.*, 2019b). Furthermore, different water resource planning methods (such as those based around bulk water balance calculations or on system simulation modelling) can inform how resources are managed in the context of these changes (Hall *et al.*, 2019b). In addition to the multiple factors influencing future public water supplies, the relative impacts are likely to vary across the UK due to variations in population density, topography, geology, the profile of economic activity, patterns of rainfall, and the water system (with some being more resilient to perturbations than others).

#### 4.9.1.3. Lock-in and thresholds (18)

The challenge remains the reliable supply to regions where a deficit is projected. Addressing this may require larger investment in areas of low rainfall, or strategic water infrastructure, such as for cross-regional transfers, all of which would have a long lead time to plan, finance and build, thus there are some early lock-in risks if early studies and plans are not implemented. Similarly, implementing transfers without sufficient long-term modelling and planning could lead the region from which water is being transferred to experience a deficit. It will likely require innovation that may become redundant over time with population shifts or have significantly increased energy requirements/risk of cascade failures (e.g. desalination plants – currently only one large plant in the UK).

Strategic water infrastructure, such as cross-regional transfers or new reservoirs, takes a long time to plan and organise; leaving such approaches too late could lead to implications for household water interruptions that could be avoided.

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<sup>13</sup> The UKCP18 60km global projections with a climate model with high climate sensitivity driven with a range of greenhouse gas concentration pathway arising from RCP8.5 emissions and accounting for uncertainties in carbon cycle feedbacks (Murphy *et al.* 2018)

#### 4.9.1.4 Cross-cutting risks and inter-dependencies (I8)

The risk of reduced water availability for public water supply interacts with risks to energy generation which is covered in Risk I9 (Risks to energy generation from reduced water availability). The implications of supply interruptions from reduced water availability as they pertain to public health and wellbeing are covered in Chapter 5: Kovats and Brisley, 2021 (Risk H10: Risks to water quality and household water supplies).

Yawson *et al.* (2019) assessed variations in potential groundwater recharge from spring barley crop fields in the fourteen UK administrative regions for 30-year periods centred on the 2030s, 2040s and 2050s using UKCP09 low, medium and high scenarios, with the medium scenario corresponding to a pathway to 4°C global warming by 2100. Agriculture covers the largest share of UK land use, with cereals accounting for the largest share of cultivated crops. Crop fields contribute to potential recharge. Groundwater is an important water resource in the UK – groundwater crucially supports public water supply, agricultural and industrial water uses, especially in central, eastern and southern England where water stresses during summer are a major concern. For all emissions scenarios, time slices and regions, the largest reduction and increase in potential groundwater recharge over baseline values were 38% and 41%, respectively. Northern Ireland, Northwest Scotland, Southwest Scotland, and Wales will have large increases in potential recharge from spring barley crop fields, while Eastern England, East Midlands, Northeast England, Southeast England, West Midlands and Yorkshire and the Humber would have the largest reductions in potential recharge. The study did not consider changes in soil management practices which can influence the spatial and temporal magnitude of potential recharge. Groundwater depletion could interact with declines in river flows to negatively affect overall public water supply in the UK. As groundwater is an important water resource in summer, a reduction in groundwater recharge could combine with hotter and drier summers to significantly impact public water supply under climate change.

This risk also interacts with risks to aquatic ecology, and risks to agriculture and other licenced abstractions (e.g. summer abstraction for agricultural irrigation and cooling water required for power stations) from reduced water availability which may compete with public water supplies for a finite resource. In 2019, the industry committed itself to achieving Net Zero carbon emissions by 2030 (Water UK, 2019) and Scottish Water (2019) are working towards becoming a Net Zero emissions business by 2040, five years ahead of the Scottish Government's 2045 target. Details of the potential changes to the industry (and any resulting changes to exposure and vulnerability to climate risk) are not clear as yet. Current work is focussing on baselining existing activities and sharing best practice. Supply options such as desalination and potable reuse are likely to increase the energy intensity of water supply compared to current baseline, due to the energy requirements of treatment. Inter-basin transfers that involve additional pumping compared to current supply may also increase energy consumption in the water sector.

WSP (2020) suggested that many climate impacts are affected by a high number of risks further up a chain of interactions. This is the case for water supply which was found to be the recipient of risk flows from interacting pathways. Most of these pathways are due to impacts on infrastructure (such as power supply failure, IT and communications disruption, and sewage flooding) leading to water supply issues. However, some causes are from the natural and built environment – for example

competing demands for water with the natural environment, drought, impacts on water quality and increased water demand due to heatwaves and very hot days. Water supply interruptions can have a subsequent impact on health and welfare (Risk H10, Chapter 5: Kovats and Brisley, 2021). The project assessed the most significant interactions relating to water supply disruptions and found that the overall risk of these interactions (based on magnitude and likelihood) are rated as low in 2020 but increase to medium by 2080. These interactions are as follows:

- Power infrastructure flooding leading to a disruption in power supply and subsequent disruptions to water supply. For example, in the 2015/16 winter floods, 350,000 people had their water supply interrupted for 17 days (costing £18/household/day).
- River, surface and groundwater flooding leading to an increase in run-off and debris causing a reduction in water quality, subsequently disrupting water supply.
- In addition, in 2050 and 2080 under a scenario of 5°C warming by 2100, the impact from increased severity of drought results in water supply disruption directly. Indirectly, an increase in the probability of drought combined with an increase in mean summer temperatures leads to soil condition and quality impacts, resulting in reduced water quality, and in turn leads to water supply disruption.
- Slope or embankment failures leading to reservoir failures and impacts on water supply. In 2018, ~1,500 people in northwest England were asked to evacuate Whalley Bridge over concerns that the dam wall of a reservoir could burst following days of heavy rain (see Case Study).

Significant interdependencies exist across the non-public water supply sectors reviewed as part of Defra (2020c). There may be unexpected water demand consequences of meeting the most ambitious decarbonisation strategies noting that locational decisions of energy companies may have a major influence on how each catchment is affected.

#### 4.9.1.5 Implications of Net Zero (I8)

Water is an energy intensive industry, accounting for approximately 6% of industrial sector energy consumption in 2019 (BEIS, 2020c), and therefore there are potential impacts on the industry from the Net Zero commitment, especially as climate change and population growth will increase water demand. Current work is focussing on baselining existing activities and sharing best practice. Supply options such as desalination and potable reuse are likely to increase the energy intensity of water supply compared to current baseline, due to the energy requirements of treatment. Inter-basin transfers that involve additional pumping compared to current supply may also increase energy consumption in the water sector. It is possible that more efficient achievement of net zero will occur through the water sector procuring net zero or net negative energy via the power sector rather than seeking to achieve local or scheme level net zero for Water Resource Zones or individual major projects.

#### 4.9.1.6 Inequalities (I8)

Regionalisation can lead to inequalities with plentiful rainfall in wetter upland areas and the increasingly drier South East. The challenge remains to ensure reliable and sufficient supply across all

regions. Any knock-on impacts to drinking water availability may disproportionately affect protected characteristics groups who require more water and those unable to afford any associated increases in cost.

#### 4.9.1.17 Magnitude scores (I8)

The magnitude scores given in Table 4.30 are based on the current and projected supply-demand balances given in the CCRA3 projections of future water availability (HR Wallingford, 2020) for the central population and 'no additional adaptation' scenario. The scores take into consideration deficits at both the water resources region and water resource zone level. HR Wallingford state (2020) that the assumption that deficits at the water resource zone can be resolved via intra-region transfers may be prohibitively expensive to achieve in practice and restricted by topography (particularly in Scotland and Wales). The water resource regions of Northern Ireland and Scotland have a current supply-demand surplus and have projected surpluses under all population and climate scenarios. Several water resource zones in Scotland are projected to be in deficit by the mid-century under both climate scenarios, with the score moving from low to medium. Surpluses are projected in all water resource zones in Northern Ireland in the mid-century, but the southern water resource zone of Northern Ireland is projected to be in deficit in both scenarios by the late century, hence the score moves from low to medium in the 2080s.

**Table 4.30** Magnitude scores for risks to Public Water Supplies from reduced water availability

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium  (medium confidence)	High  (medium confidence)	High  (medium confidence)	High  (medium confidence)	High  (medium confidence)
<b>Northern Ireland</b>	Low  (medium confidence)	Low  (medium confidence)	Low  (medium confidence)	Medium  (low confidence)	Medium  (low confidence)
<b>Scotland</b>	Low  (medium confidence)	Medium  (low confidence)	Medium  (low confidence)	Medium  (low confidence)	Medium  (low confidence)
<b>Wales</b>	Low  (medium confidence)	Medium  (medium confidence)	Medium  (medium confidence)	Medium  (medium confidence)	Medium  (medium confidence)

England has a nominal present-day supply-demand deficit in the South East water resource region

and has been scored as medium magnitude due to the population exposed in this region. Deficits at the water resource region scale increase under all climate scenarios, with the 2080s and 4°C world seeing all regions in England at deficit. All water resource regions in Wales have a present-day supply-demand surplus, hence the low magnitude score. Supply-demand deficits are apparent in the southeast of Wales under all future scenarios, although the majority remains in surplus (medium magnitude). Confidence is given as medium where the magnitude score is based on projections for the water resource region (concordant with the CCRA3 future water availability assessment), and low where based on water resource zones, given the uncertainty around the feasibility of intra-region transfers.

#### 4.9.2 The extent to which current adaptation will manage the risk (I8)

##### 4.9.2.1. Effects of current adaptation policy and commitments on current and future risks (I8)

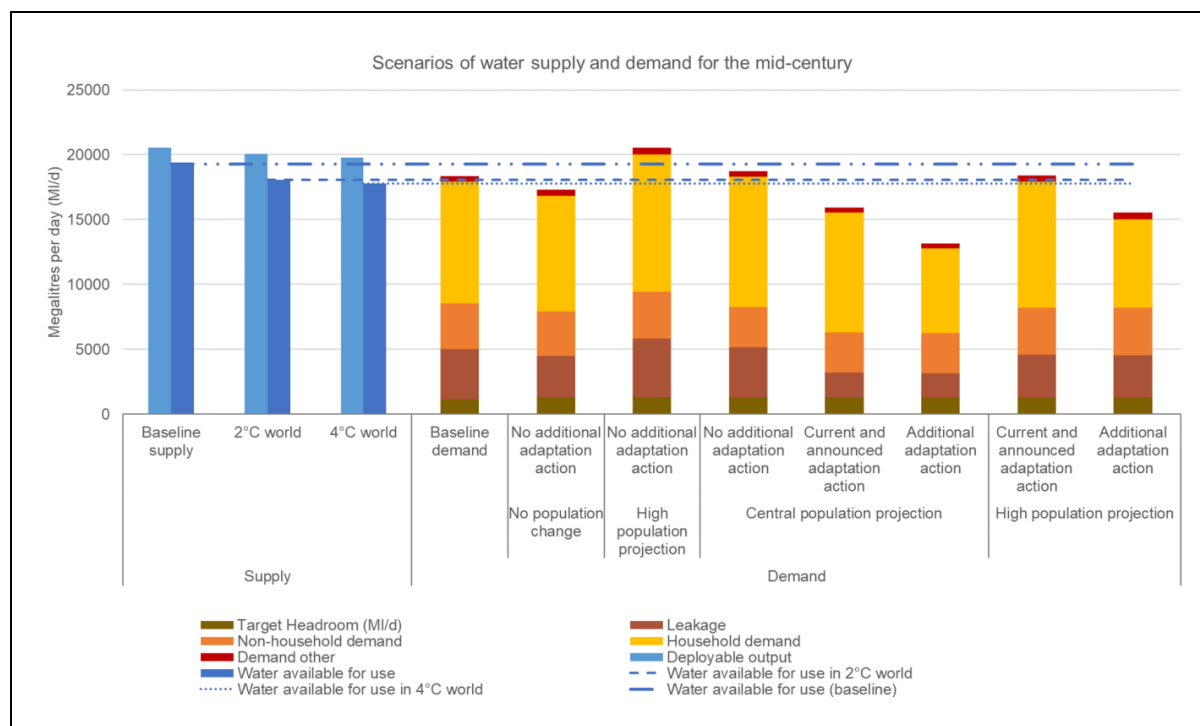
###### 4.9.2.1.1 Legislation (UK)

Water supply is regulated under the Water Industry Act 1991 (as amended) and the Water Resources Act 1991 (as amended – England and Wales), the Water Resources (Scotland) Act 2013, and the Water and Sewerage Services (Northern Ireland) Order 2006. The Water Act 2014 introduced a ‘resilience duty’ that requires Ofwat and the Secretary of State/Welsh Ministers to secure the long-term resilience of water company supply systems and ensure that water companies take steps for the purpose of enabling them to meet, in the long term, the need for the supply of water. Water companies already plan for droughts as part of their Business Plans, and the Water Act also includes an additional power for the Secretary of State/Welsh Ministers to direct water companies to plan for droughts of a specified magnitude.

###### 4.9.2.1.2 UK-wide adaptation for mid-century projected deficits (demand-side adaptation)

Figure 4.7 shows a selection of the adaptation scenarios that were simulated for the mid-century time period at the UK scale presented in the CCRA3 projections of future water availability (HR Wallingford, 2020). The deployable output and water available for use under the baseline, 2°C and 4°C worlds is given on the left-hand side in dark and light blue. The demand under a variety of demand-side adaptation and population scenarios is given on the right-hand side (the components of this demand such as household and non-household demand are also given). The water available for use in a 2°C and 4°C world is represented by horizontal blue dotted lines. If demand on the right-hand-side of the graph is below these lines this represents a surplus at the national scale.

The current and announced demand-side adaptation scenario, which has been designed to reflect current levels of policy ambition in the water sector, sees a projected surplus at the national scale in the mid-century period under both 2°C and 4°C worlds with a central population estimate. Under a high population scenario, the planned adaptation scenario does not go quite far enough to balance projected deficits due to climate change. The influence of additional demand-side adaptation actions over and above what is planned, through reducing leakage and per capita consumption, are evident when comparing the scenarios that use the central and high population projections.



**Figure 4.7.** Scenarios of UK water supply and demand in the mid-century for different climate, adaptation and population scenarios. Only demand-side adaptation actions are included in the scenarios above. Reproduced from HR Wallingford (2020).

Figure 4.8 shows the projected supply-demand balances at the water resource region scale by mid-century under a central population scenario. The left-hand map presents balances for a 2°C world with current and announced demand-side adaptation actions, the middle map shows a 4°C world with current and announced demand-side adaptation, and the right hand map shows a 4°C world under the ‘additional adaptation’ (demand-side) scenario. The current and announced demand-side adaptation actions are projected to result in surpluses for all regions in a 2°C, central population world, but would result in a deficit for Water Resources South East in a 4°C, central population world. The ‘additional adaptation’ scenario would result in surpluses for all regions at the mid-century.

#### 4.9.2.1.3 UK-wide adaptation for late-century projected deficits (demand-side adaptation)

Figure 4.9 shows scenarios for the late-century time period at the UK scale presented in the CCRA3 projections of future water availability (HR Wallingford, 2020). Here, the current and announced adaptation scenarios use the per capita consumption values in the latest water company resource plans up to 2044/45 and then remain the same for the rest of the century. Average per capita consumption is projected to be around 122 l/h/d (England ~120 l/h/d; Wales ~105 l/h/d; Scotland ~156 l/h/d and Northern Ireland ~152 l/h/d) by mid-century. These figures are based on the water companies’ final plans in England and Wales (which include companies’ ambitions for reducing per capita consumption). As final plans were unavailable for Scottish Water and Northern Ireland Water and no intention to significantly increase meter penetration across households to reduce household consumption has been reported, baseline plan values were used (leading to higher per capita consumption compared to England and Wales. In the analysis, leakage was reduced to 50% of

baseline values by the mid-century were then fixed to the end of the century across all regions.

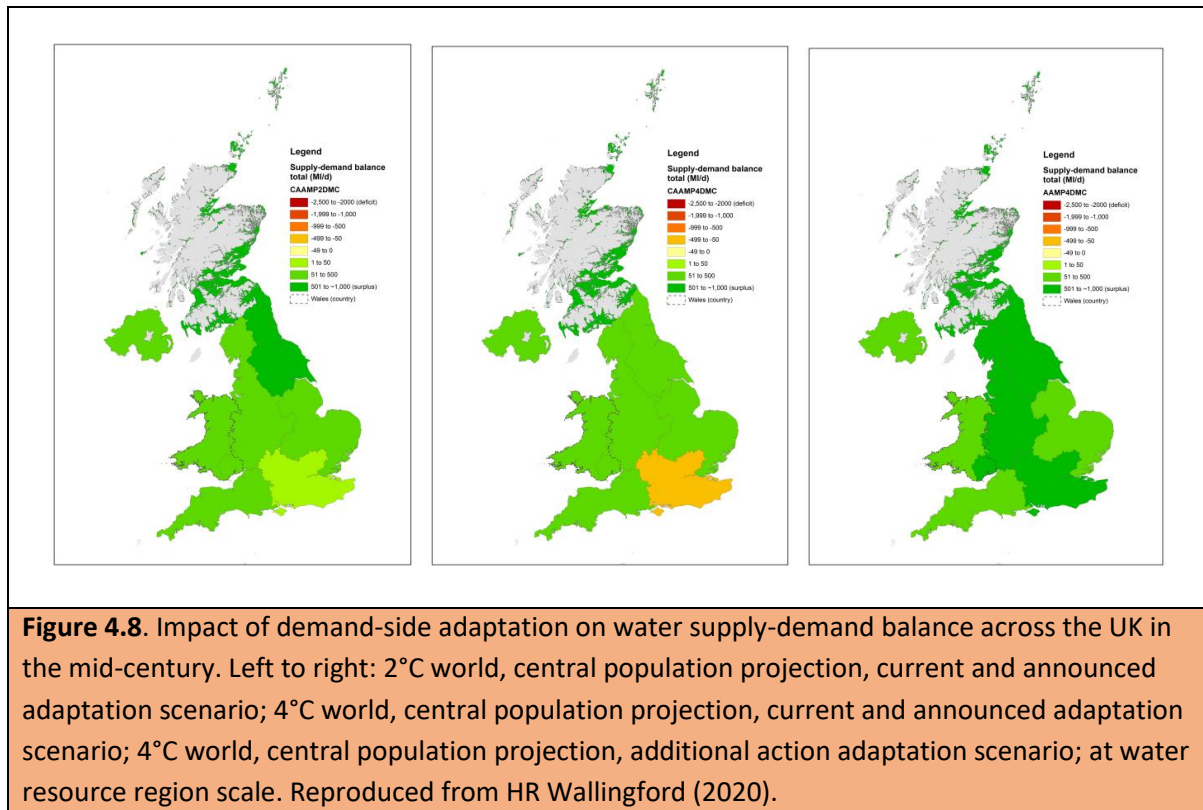
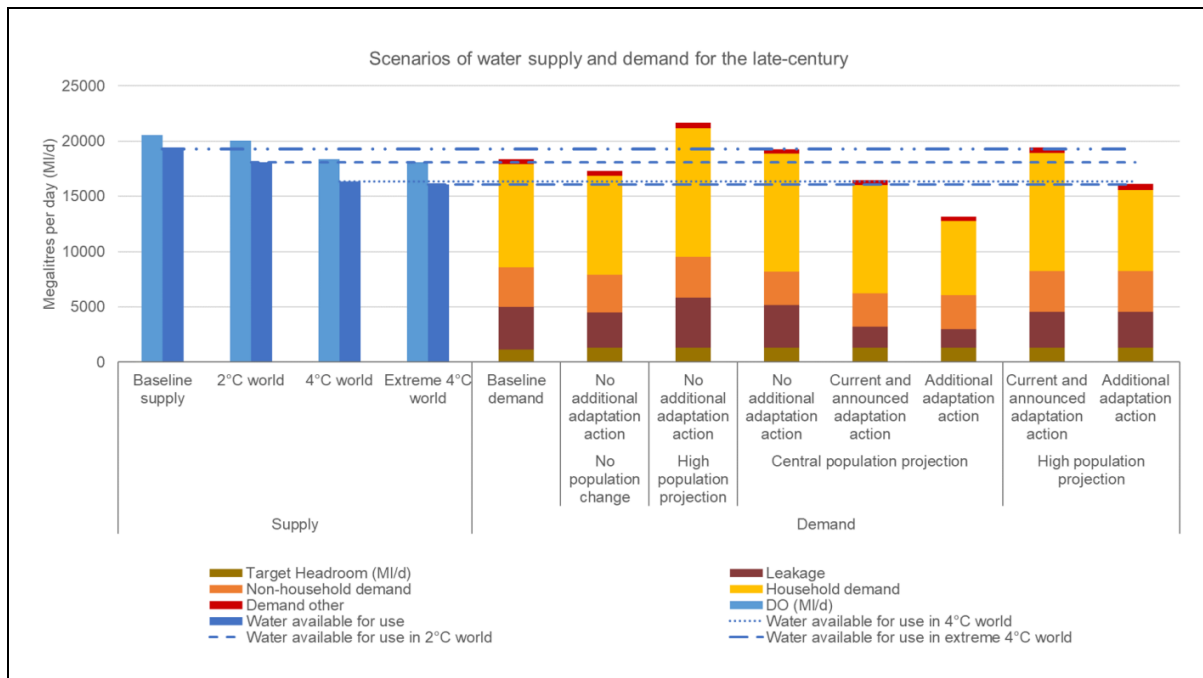
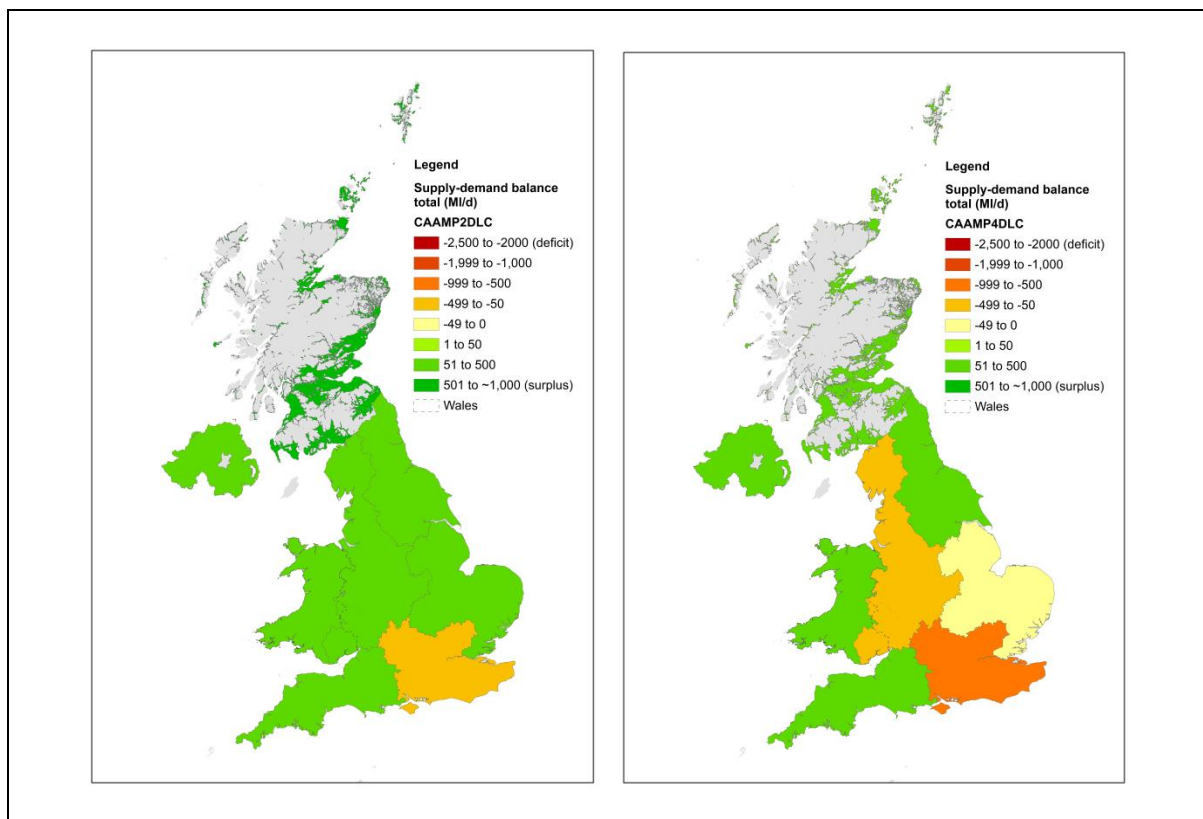


Figure 4.9 shows that for 2°C and 4°C worlds under a central population scenario, current and announced demand-side adaptation actions are projected to result in a supply-demand surplus in the late 21<sup>st</sup> century. Under a high population scenario, the current and planned scenario is not enough to manage the projected deficits and only the additional action scenario (i.e. a more ambitious level of demand-side adaptation than is currently planned), results in a UK-wide supply-demand balance surplus by late-century (both 2°C and 4°C worlds).

Figure 4.10 shows supply-demand balance for different water resource regions around the UK in the late-century, in a 2°C (left hand map) and 4°C (right hand map) world, under a central population projection and with the current and announced demand-side adaptation action scenario. For the 2°C world, current and announced demand-side adaptation results in a deficit for the Water Resources South East region. The deficit for this region is of the order of 310 Ml/d (the supply for a little more than 2.1 million people every day based on present day levels of UK water consumption). For a 4°C world, the South East is in deficit by nearly 750 Ml/day. In addition, Water Resources West has a projected deficit of 180 Ml/d, with Water Resources East at 15 Ml/d. It is estimated that by the late century, the projected impact of climate change on the supply-demand balance for the UK is around 40% of the potential impact of population growth. Deficits are also projected in the southeast of Wales. It should be noted that at a country scale, only England has projected deficits due to climate change under this scenario.



**Figure 4.9.** Scenarios of UK water supply and demand by late-century for combinations of climate, adaptation and population scenarios. Only demand-side adaptation actions are included in the scenarios above. Reproduced from HR Wallingford (2020).



**Figure 4.10.** Supply-demand balance in the late 21<sup>st</sup> century, in a 2°C (left) and 4°C (right) world, central population projection and current and announced adaptation action scenario, at water resource region scale. Grey indicates areas reliant on private supply. Reproduced from HR Wallingford (2020).



England shows the largest range in supply-demand balance. HR Wallingford (2020), state that this is most likely due to the fact that more sources are yield-constrained in England and therefore cannot provide any more water than they currently do without exceeding environmental protection measures. In addition, the greater application of sustainability reductions in England compared to the other countries increases dependency on the remaining abstractions, meaning any change in river flows as a result of climate change will impact upon the deployable output of these sources.

It must be noted that Wales and Northern Ireland water resource plans model climate change impacts to the 2030s and 2020s respectively. It is highlighted in the HR Wallingford (2020) report on water resources that this may not be far enough into the future to identify thresholds at which yield may become the dominant factor on resource availability, and that this relative lack of climate sensitivity permeates through the CCRA3 water resources assessment. It is argued that this lack of climate sensitivity may be genuine, although could be due to the water companies not projecting far enough into the future to identify tipping points in the systems' resilience.

#### 4.9.2.1.4 Supply-side adaptation

The CCRA3 water resources project (HR Wallingford, 2020) also modelled the potential impact of water supply-side adaptation options and inter-regional transfers on future supply-demand balances. The analysis utilised the preferred supply options identified by water companies in the draft WRMP19 plans available at the time of the analysis. These total around 940 MI/d planned for by water companies in England and Wales. 430 MI/d of water in transfers between regions were also identified. These were applied to the mid- and late-century periods in the analysis.

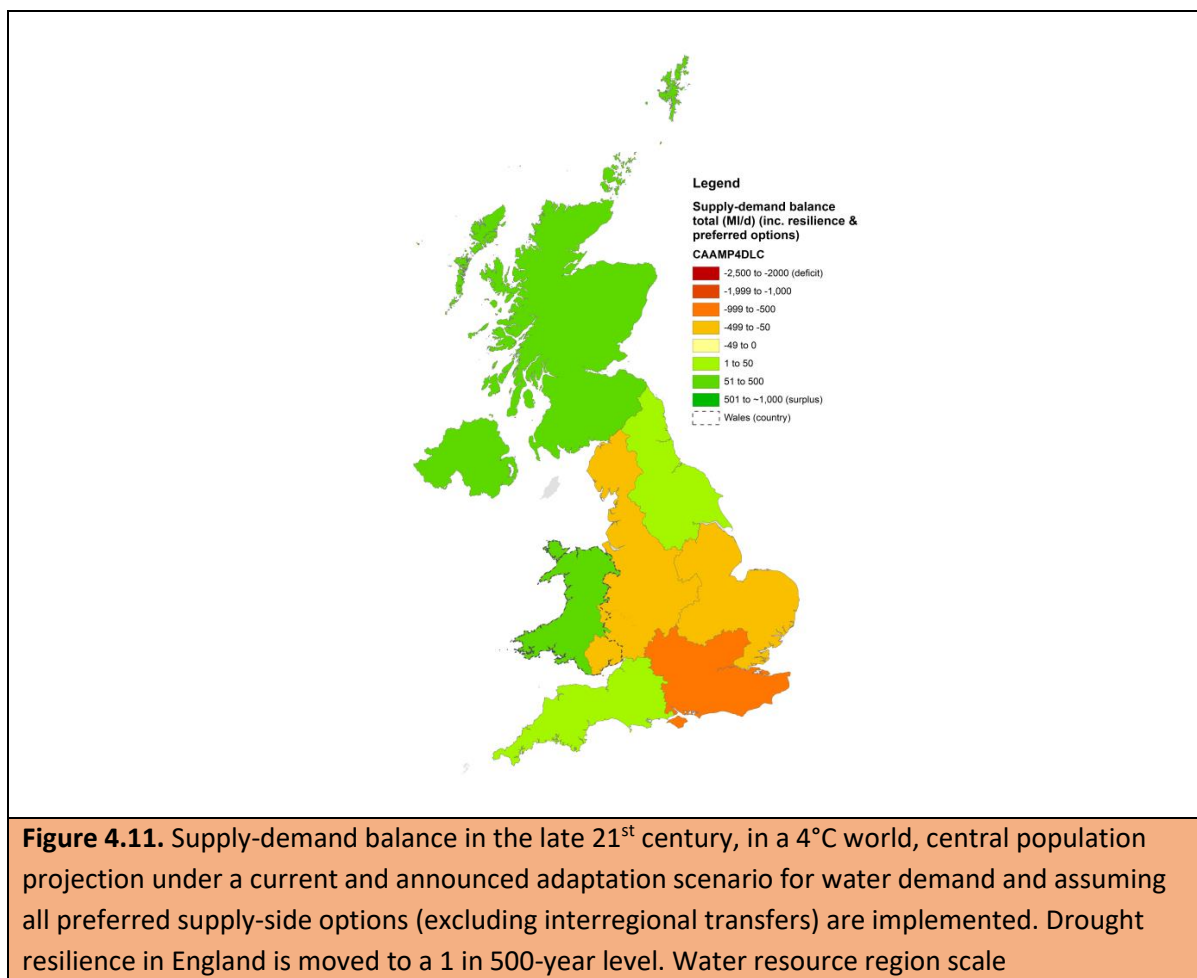
By applying the identified additional water to use to the supply-demand balance scenarios for England and Wales and assuming no additional demand-side adaptation, the preferred supply-side measures or transfers, when utilised in isolation, were projected to not be sufficient in reducing the supply-demand balance deficit in Water Resources South East, Water Resources East or Water Resources West, across the majority of the scenarios in the mid- or late-century.

When taking demand side and supply-side adaptation measures together, HR Wallingford report surpluses in England apart from a minor deficit in Water Resources West by late century in a 4°C world. When inter-regional transfers are included, the deficit in Water Resources West increases. It is assumed in this analysis that Water Resources West and Water Resources South East are linked by a large potential transfer option, from the River Severn to the River Thames. It is however, pointed out that the identified supply-side adaptation options may not be cost-effective solutions, particularly in regions such as the South East.

#### 4.9.2.1.5 Combined impact of increased drought resilience and supply and demand options

HR Wallingford (2020) modelled the effect of moving to a 1 in 500-year level of resilience to drought and the associated deployable output cost for water resource regions in England (including Water Resources West which supplies parts of South East Wales – Figure 4.11). All preferred supply-side adaptation options (but not inter-regional transfers) are utilised, along with current and announced demand-side options. It is clear that moving to a 1 in 500-year level of resilience creates significant

reductions in deployable output at the regional level, particularly for Water Resources South East. As the analysis is at the water resource region scale, it is unclear whether the nominal deficits would affect the Welsh part of Water Resources West.



**Figure 4.11.** Supply-demand balance in the late 21<sup>st</sup> century, in a 4°C world, central population projection under a current and announced adaptation scenario for water demand and assuming all preferred supply-side options (excluding interregional transfers) are implemented. Drought resilience in England is moved to a 1 in 500-year level. Water resource region scale

#### 4.9.2.1.6 Policy in England and Wales

Regulators use the WRMPs to assess the measures companies need to undertake to manage the risk of supply-demand deficits. Water companies are required to prepare WRMPs every five years. These set out how water companies plan to balance water supply and demand over the next 25 years, taking into account the effects of climate change as well as other factors such as population growth and reductions in abstraction required to improve the ecological condition of rivers and lakes. Water companies also submit their business plans to the economic regulator as part of a five-yearly process known as a Periodic or Price Review. Price reviews set the price, service and incentive package for a five-year period. They set out the allowed revenues, expected levels of service and the set of financial and reputational incentives for each company.

CCC (2019b) scores the English water industry's adaptation plans as 'high' stating that the WRMPs set out how water companies have committed to more ambitious targets to reduce leakage and many have considered possible options for new water supply infrastructure and improving resilience to extreme weather. Progress in managing the risk is scored as 'medium', stating that after large

reductions in leakage during the 1990s, there has been slower progress. Nonetheless water companies are expected to deliver a 15% minimum reduction in leakage by 2025 (Ofwat, 2019) and have committed to halving leakage by 2050.

The Environment Agency's recent National Framework (2020c) sets out England's water needs to 2050. The aim of the framework is to ensure that the best strategic solutions are taken for the country as a whole, as it is acknowledged that this may not be achieved through individual water company plans. Regional plans by groups such as Water Resources East and Water Resources South East will be prepared based on this framework by September 2023. The document sets out that a total of 3.4 billion additional litres (3,400 Ml) will be needed between 2025 and 2050. The framework lays out measures for meeting this figure including reducing demand to an average of 110 litres per person per day by 2050, improving water efficiency across all sectors, working with water companies to halve leakage rates by 2050, developing new supplies such as reservoirs, water re-use schemes and desalination plants, making it easier to move water through regional water transfers, and reducing the use of drought measures that can impact the environment. The government has committed to set an ambitious personal water consumption target for England in the 25 Year Environment Plan (Defra, 2020).

#### 4.9.2.1.7 Wales

In Wales, the 2019 climate change adaptation plan, *Prosperity for All: A Climate Conscious Wales* (Welsh Government, 2019b) and the Welsh Government's Water Strategy for Wales set out high level strategies and plans for the water sector. RBMPs and WRMPs provide an overall indication of water supply and demand based on UKCP09. However, the next round of WRMPs will be based on UKCP18. Four areas of concern related to climate change in terms of demand and supply are North Eryri/Ynys Mon in North Wales, the SEWCUS area in South Wales covering Cardiff, Newport and the Valleys, Tywyn Aberdyfi in West Wales, and Pembrokeshire. Two water deficit zones have also been identified using climate projections. Current intervention in the Welsh Government's adaptation plan is not specific to water supplies but supports management of this risk through the development of ecological resilience at a water catchment level.

In its 2019 Annual Report, the National Infrastructure Commission for Wales (2019) recognises the risk to water supply for the UK as a whole but notes the particular issue for Wales of the potential future need to transfer water supply to England. It also recognised the demand challenges found in growing urban centres. This is further mirrored in policy 1 of *Future Wales: National Plan 2040* (Welsh Government, 2021a).

#### 4.9.2.1.8 Northern Ireland

The Water and Sewerage Services Act (NI) 2016 requires the preparation and review of a Water Resource and Supply Resilience Plan (WR&SR Plan), which takes into account adaptation measures in response to climate change predictions to calculate supply/demand balance for the water supply. At a regional level in Northern Ireland, in 2014 the Northern Ireland Executive approved the development of a Strategic Drainage Infrastructure Plan (SDIP) for Belfast, an outcome of a consultation on 'Living with water in Belfast'.

Northern Ireland Water (NI Water) has a legislative requirement to produce a Water Resource Management Plan (WRMP) and a Drought Plan as part of its forward planning process. These two plans have been combined into the WR&SR Plan. The WR&SR Plan shows how the company will manage and develop water resources to make sure there is enough water to meet future supply needs. The WR&SR Plan takes into account changes in population, housing and water usage, and incorporates predicted changes to the climate. This includes how water supplies would be maintained during critical periods such as severe winters and droughts, and also includes a drought plan. Northern Ireland has a long-term sustainable water strategy. NI Water recommends revisiting the plan using UKCP18 climate change projections to provide an improved understanding of future hydrological conditions in Northern Ireland.

#### 4.9.2.1.8 Scotland

In Scotland, SEPA's Water Supply and Wastewater Sector plan (2019) has the high-level aims to:

- inspire and enable communities and businesses to take action to prevent water being wasted and to use it more efficiently,
- make low water use designs, including designs involving the use of recycled waters and rainwater, the norm for new developments,
- ensure opportunities to reduce leakage are taken when buildings are being refurbished or other infrastructure is being maintained or renewed,
- enable Scottish Water to find new ways of efficiently detecting and fixing leaks, targeting areas where the ability to meet demand for drinking water is threatened by climate change and population growth or where opportunities to reduce energy and chemical use are greatest.

#### 4.9.2.2 Non-government adaptation (I8)

Water companies are investing to improve resilience, but it is not clear if this investment will be adequate to address future risks, particularly in the context of a 4°C global temperature scenario. This is because although the planned level of adaptation can be modelled as shown above, adaptation measures are not funded more than five years ahead. Indeed, there is uncertainty whether the current scenarios are sufficient to cover future risks, although as WRMPs are revised on a five-yearly basis, there is a framework within which future risks will be mitigated. There is uncertainty regarding future funding, which is subject to the Price Review process.

Ofwat (2020) sets out spending for water companies over the subsequent five years. Several of the features of the latest round have implications for resilience and adaptation, with allowances for resilience schemes, metering and new supply options. English and Welsh companies and competitively appointed providers are allowed to invest £2.6 billion in protecting customers and the environment from the risks of extreme weather conditions (such as drought and floods) and critical asset failures. Companies also plan to invest £650 million in the installation of at least 2 million new water meters over the 2020-25 period (smart meter installations should also provide more insight into consumer demands and help identify leaks). Up to £469 million has been allocated to help

companies work together on solving long-term drought resilience challenges, through measures such as reservoirs and the national transfers of water from the northwest to the southeast of England. This will be overseen by Ofwat, in collaboration with the Environment Agency and the Drinking Water Inspectorate, via RAPID, the Regulatory Alliance for Progressing Infrastructure Development. RAPID has been formed to help accelerate the development of new water infrastructure and design future regulatory frameworks, working with water companies to promote the development of national water resources infrastructure that is in the best interests of customers and the environment. Thus, RAPID will help to meet the challenges articulated in documents such as the WRLTPF (Water UK, 2016).

Separate evidence from the National Infrastructure Commission (2018b) found that ‘maintaining the current levels of resilience (to the worst historic drought) in the face of rising population, environmental and climate pressures to 2050, would require additional capacity of about 2,700-3,000 MI/day in England. An additional shortage of between 600 and 800 MI/day would result from a severe drought (0.5% annual probability), and between 800 and 1,000 MI/day in an extreme drought (0.2% annual probability). The ranges reflect uncertainty about the impact of changes in population and climate, but the overall additional capacity required is between 3,500 and 4,000 MI/day.’ Additional capacity of 4,000 MI/day should provide resilience to an extreme drought until 2050 even with high climate change and population growth, with most of it likely to be needed by the 2030s. Much of this additional capacity would still be needed even assuming medium climate and low population growth. In any case, the full 4,000 MI/day is likely to be needed within a few decades of 2050 so can be considered ‘low regret’. This figure is around 20% of baseline (2019) deployable output in the CCRA3 water resources analysis (HR Wallingford, 2020), demonstrating the considerable scale of the challenge. For climate projections, the study uses: ‘Central: medium emissions Future Flows, average water balance scenario, Dry: medium emissions Future Flows, with less water in the South East’. For socio-economic scenarios, ‘Population growth: Low: ONS 2014-based low migration population projection, High: ONS 2014-based high fertility population projection’ scenarios are used. However, an initial analysis of the 2019 draft WRMPs by CCC (2019b) shows that around 1,200MI/d will be delivered through new infrastructure, roughly in line with the NIC’s recommendation.

Hutchins *et al.* (2018) assess how water resources in the Thames river basin will be affected by three future climate and planning scenarios for the 2030s and 2080s. The two most extreme scenarios (based on RCP8.5 and related socio-economic assumptions) could not be supported by current management strategies to meet water demand. To satisfy these scenarios, transfer of river water from outside the Thames river basin would be necessary. The authors conclude that the projected climatic changes under the most extreme RCP (8.5) might result in drying of the river (i.e. the River Thames) for part of the year which could only be mitigated with significant changes in water management through building a new reservoir or water transfer from outside the catchment. For socio-economic scenarios, the study uses three scenarios developed in the MARS project: one an extension of present-day rates of economic development, the others representing more extreme and less sustainable visions.

#### 4.9.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I8)

The adaptation scores below are based primarily on the HR Wallingford (2020) analysis on the potential impact of current and announced demand- and supply-side options on supply-demand balances by the late-century under a central population estimate.

The current and announced adaptation scenario in the HR Wallingford analysis based on demand management only is on the whole successful at managing risks to public water supplies by the mid-century and late-century across Scotland and Northern Ireland, so there is not deemed to be a shortfall for public water supplies in these nations (though note that both may experience significant risks to private water supplies, this is covered in risk H10). HR Wallingford (2020) show that current planned and announced demand-side adaptation actions are sufficient to bring the vast majority of Wales into surplus. However it must be noted that part of the mainly English water resource zone, Water Resources West, supplies parts of South East Wales, which may be in deficit in certain scenarios (although it is not indicated whether this will cause deficits in those water resource zones in Wales). It is the authors' view that sufficient evidence is not available to determine a future medium magnitude impact on Wales from the projected deficits in Water Resources West, but it is noted that this should be explored further in future projections. Low confidence is given in this assessment as a result.

In England, the current and announced adaptation scenario is less successful in reducing the magnitude of deficits to a low magnitude by late-century (hundreds of thousands of people could still be affected by deficits across England). When considering supply-side and demand-side measures in combination, it is suggested by HR Wallingford (2020) that surpluses are theoretically possible for the vast majority of regions, however it is argued that the identified supply-side options are likely not to be a cost-effective way to create surpluses, particularly in regions such as the South East. It should also be noted that the analysis is aggregated at the regional level, which may hide deficits at the water resource zone level. It is the authors' view that transfers should not be relied upon as the means of adaptation in the late 21<sup>st</sup> century for England as they are not currently included in planned adaptation. While a lot of positive adaptation has been announced which is projected to manage the risk, the announced adaptation is ambitious relative to present day progress with leakage and per capita consumption (PCC) reduction, and there remain concerns regarding water availability in the late century and the ability of transfers to cover deficits, therefore it is concluded that the risk will be partially managed in England.

Regarding the climate impacts on reservoir integrity, climate change projections are presently not used to inform the risk assessment or inspection regime for reservoirs in England, Northern Ireland, Scotland or Wales and remains an area for future attention.

## 4.9.2.2 Adaptation Scores (I8)

<b>Table 4.31</b> Adaptation scores for risks to Public Water Supplies from reduced water availability			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Medium confidence)	Yes (Medium confidence)	Yes (Medium confidence)	Yes (Low confidence)

## 4.9.3 Benefits of further adaptation action in the next five years (I8)

## 4.9.3.1 Additional planned adaptation that would address the adaptation shortfall (I8)

The CCRA3 water resources project (HR Wallingford, 2020) finds that the only scenarios that result in a significant UK-wide supply-demand balance surplus are ones in which additional adaptation action is taken to reduce demand or where the current and announced adaptation scenario is applied to the central population. This scenario includes the water companies' own ambitions for reducing per capita consumption for England and Wales, baseline values were used for Scottish Water and Northern Ireland water as those companies have reported no intention to significantly increase meter penetration in households or other measures to reduce household consumption. Considering reservoirs, the routine use of climate projections and their potential impacts on the bund and spillways during safety inspections and mid- to long-term planning would better protect them from failures exacerbated by climate change. Establishing appropriate leakage targets using a sufficiently wide assessment framework considering all potential users may improve multi-sector resilience and economic efficiency of water and water rights use. Defra announced it is looking to bring in a statutory long-term water demand target by October 2022. The target will likely combine demand on public water supplies from households, business and due to leakage.

## 4.9.3.2 Indicative costs and benefits of additional adaptation (I8)

There are estimates in the literature on the benefits of further action. In terms of the supply side there are several studies that have considered additional measures, but these focus more on drought. Water UK (2016) estimated that a 'twin track' approach of demand management coupled with development of new resources and potential transfers is the most suitable strategy for providing drought resilience in the future. They estimated that total costs per annum for all potential future scenarios (under the business as usual base demand management strategy) to maintain resilience at existing levels in England and Wales are between £50 million and £500 million per annum in demand management and new water resource options. If resilience to 'severe drought' is adopted, this increases to between £60 million and £600 million and for resilience to extreme drought, between £80 million and £800 million per annum. The National Infrastructure Commission (2018b) estimated that in England alone the total costs between 2020 and 2050 of implementing emergency measures to provide household water supply during a 0.5% drought, weighted by the occurrence probability, range between £13 and £16 billion. The total costs over the same period of implementing emergency measures against a 0.2% drought range between £21 billion and £27 billion (costs on a present value basis (2018 prices) weighted by the occurrence probability). Atkins

(2018) used cost benefit analysis to build marginal abatement cost curves of emergency measures, i.e. when drought severity is beyond the capacity planned for through long-term water resources planning. This included examples for the Thames Basin. The results indicate that many emergency measures would be challenging to implement, provide uncertain yields and incur significant costs (Atkins, 2018).

There is also a suite of demand side measures that can be introduced by homes, many of which are no-regret and low-regret. Water UK (2016) assessed a twin track approach of demand management coupled with appropriate development of new resources and potential transfers as being the most suitable strategy for providing drought resilience in the future. They estimated that total costs per annum for all potential future scenarios (under the business and usual base demand management strategy) to maintain resilience at existing levels in England and Wales are between £50 million and £500 million per annum in demand management and new water resource options. If resilience to 'severe drought' is adopted, this increases to between £60 million and £600 million and for resilience to extreme drought, between £80 million and £800 million per annum. There are several studies that have looked at demand side measures for households that identify a large number of low- and no-regret options. The study by ARUP (2008) looked at a range of water saving measures, and estimated costs and pay-back times. A similar study was commissioned by the CCC (Davis Langdon, 2011) looking at cost-effectiveness of alternative household options, and this was updated by Wood Plc (2019), updating a previous cost-curve study. These studies identify estimated measures with benefit to cost ratios above 1 for different house types, comparing new-built vs discretionary retrofit. The study provides unit-cost estimates for different measures, and calculated cost-curves to show their relative cost-efficiency. When considering wider benefits from a societal perspective (including avoided GHG emissions), additional no-regret measures are identified. Generally, end-of life upgrades and measures installed in new builds were more cost-effective compared to retrofits. These studies highlight the high economic benefits of further action.

Research by Artesia (2019) for Water UK assessed the savings, costs and benefits of 18 water demand reduction interventions. It was estimated that with concerted effort by government departments, regulators and water companies, £64 benefit for every £1 spent could be achieved. The report found that the best strategy to maximise demand reductions involved mandatory water labelling and increased smart metering (above that in current water company plans). It was estimated that a 2,300 MI/d reduction in demand beyond current ambitions could be achieved through these measures.

Additional information on research regarding the costs and benefits of additional measures is set out in Table 4.32 below.



**Table 4.32** Costs and benefits of implementing additional adaptation in next 5 years

Strategy	Benefits	Costs	Source
Mandatory government led scheme to label water-using products, linked to tightening building Regulations and water supply fitting regulations	Reduce consumption by an additional 31 l/h/d or 2,012 MI/d by 2065.	£64 benefits for each £1 spent	Energy Saving Trust, (2020)
The National Infrastructure Commission recommended building resilience to 1 in 500-year drought. Supply infrastructure that supplies a further 1300MI/day will need constructing.	Net increase of at least 4000 MI/d based on the medium emission scenario.	Between £18 billion and £22 billion over 30 years to provide proactive, long-term resilience.	(NIC, 2018b)
Metering aim (95% of households) by 2030-2035.	Save 400-800 MI/d of water in 2050 (depending on the meter used). The proportion of households with metres in 2017 was 54%.	Unknown	(CCC, 2019a)
Demand management and new water resource options.	Increase resilience. Additional costs of becoming resilient to 'severe drought events' are becoming less than £4 per household-customer per year.	Between £50 million and £500 million per annum for severe drought resilience. Between £80 million and £800 million per annum for extreme drought resilience.	(Water UK, 2016)

#### 4.9.3.3 Overall urgency scores (I8)

More action is needed to address future supply-demand deficits in England, identified by the updated future water availability results discussed above. Urgency scores for Scotland and Northern Ireland are 'sustain current action', owing to only a low magnitude of risk of water deficits being

projected by the end of the century in the highest likely scenario on the basis of current planned adaptation measures. The urgency score for Wales is also 'sustain current action', although is noted that there is a need to determine any potential deficit in Wales from the mostly English Water Resources West region.

**Table 4.33** Urgency Scores for risks to Public Water Supplies from reduced water availability

Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	Sustain current action	Sustain current action	Sustain current action
Confidence	Medium	Medium	Medium	Medium

Actions to reduce future risk have been identified in the Environment Agency's national framework for water resources (2020c). In terms of demand, the Environment Agency state that the regional groups should:

- contribute to a national ambition on average PCC of 110 l/p/d by 2050 (reviewed every 5 years),
- reduce the water lost from networks by 50% by 2050 from a baseline of 2017 to 2018,
- pursue ambitious reductions in non-household demand and contribute to the evidence available on the potential savings (including working with non-household water retailers and new appointments and variations (NAVs)),
- identify ways to reduce water use outside of public water supply,
- explore how they can coordinate the use of temporary use bans (TUB) among the water companies,
- review their planned frequencies of use for TUB and non-essential use bans (NEUB) in the light of the planned increase to drought resilience.

To support this, the Environment Agency request that the Government and regulators should introduce a new monitoring and reporting framework to monitor and report on progress on demand management. In terms of supply, the Environment Agency state that regions should:

- scope a wide range of supply options, such as reservoirs, water reuse and desalination (determining how long each would take to implement to allow options to be brought forward if required),
- explore the strategic options funded as part of Ofwat's gated process,
- identify new options not included in current plans and engage in the catchment-based approach (particularly priority catchments), to develop cross-sector options with broader societal benefits,
- investigate the potential for increasing connectivity within and between regions (including longer distance transfers (over 100 km), and shorter transfers that increase resilience to interruptions in supply),
- When exploring transfers, regional groups should consider the potential to make them reversible so that they can increase the resilience of both parties, be clear on how transfers would be used during droughts and work with the DWI and RAPID to ensure planned

transfers are feasible and that any issues are carefully managed.

#### 4.9.4 Looking ahead (I8)

A useful additional piece of analysis for determining potential future risk and benefits of adaptation would be breakdowns across the UK of what could be achieved with different levels of adaptation, broken down further by benefits achieved from reducing leakage, adding new infrastructure (including desalination) and reducing demand respectively. It is clear that additional water demand management is an important component element of adaptation. This would include decentralised supply options (rainwater harvesting and greywater reuse), as well as water efficiency standards in new homes and retrofits. Widespread rainwater harvesting holds potential for adaptation to increased surface water flooding. Ricardo's 2020 report for Waterwise overviews the costs and benefits of rainwater harvesting and greywater reuse for flooding and water resources.

Transformational adaptation could include construction of strategic resources that would enable adaptation over the long-term (the last major phase of strategic resource development was in the 1960s and 70s to serve growth). Similarly, universal metering, and ultimately smart metering, could significantly assist with controlling demand.

Further work is needed on the assessment of the costs of adaptation options (cost/benefit analysis), including the feasibility of water transfer from regions of surplus to regions of deficit. CCRA4 would also benefit from testing the assumption that under projected climate change scenarios, water can be freely transferred between existing supply systems. It should also be noted that spatial changes in demand brought about by shifts in working patterns brought about by COVID-19 (as well as broader socio-economic trends) should be taken into consideration in future assessments. Frontier Economics (2020) observed that changes in consumption as a result of the pandemic may put extra stress on certain parts of the water network in the long term.

There are potential multi-sector benefits of solutions with flood resilience schemes such as wetlands and peat bogs. Looking ahead at the 25 Year Environment Plan range it may be worth exploring a more natural capital approach, placing more value on ecosystem services.

#### 4.10. Risks to energy generation from reduced water availability (I9)

The electricity supply industry dominates surface and groundwater abstractions in England, accounting for 49% of estimated actual abstraction in 2016 and 2017 and 65% of estimated licenced abstraction; 82% of abstractions from tidal waters and 30% from non-tidal waters (Defra, 2019a). The statistics include both thermal and hydropower. While hydro-electric plants are considered separately in Risk I6, in terms of other electricity generation, thermal power generators (including energy from waste plants) sited inland are the main type of generation vulnerable to reduced water supply. Around 60%, by capacity, of all thermal power plants in the UK are cooled with sea and tidal water, including all nuclear generation with the remaining plants reliant upon freshwater for cooling (BEIS, 2020b). While thermal plants cooled by tidal waters may not necessarily face restrictions in

water availability, the operation of all plants may face restrictions on discharging cooling water in order to protect aquatic ecology. This is a different risk than water availability but is also related to warmer temperatures and similarly may restrict plant output.

The oil and gas industry also require water for operation at existing locations in the UK, their offshore and coastal locations enable the use of salt water for many operations, however international supply chains may be vulnerable to restrictions in freshwater availability (Holland *et al.*, 2015). Test sites for shale gas also use freshwater for the fracturing process; this industry is not yet established in the UK so does not at present require significant volumes of water, however, were it to grow, its water requirements should be reassessed.

This section has focussed on risks to thermal plants, as these are most relevant to the UK's current energy portfolio. Current risks to thermal plants arise from restrictions to either abstracting (freshwater reliant plant) or discharging water (both tidal and freshwater plant) due to periods of low rainfall and/or elevated temperatures. Significant interruptions to thermoelectric generation have not been reported to date, therefore the current risk across the UK is deemed low. Analysis of future risks to the sector suggest there are particular areas of England where existing inland thermal plants are likely to be exposed to reduced water supply. The effects of climate change on discharge constraints on thermal plants are out of the scope of this assessment, however, relevant impacts relate to regulatory standards as well as to the wider effects of climate change on water quality and aquatic ecosystems – such as temperature, oxygen levels, flow patterns and salinity profiles (Arnell *et al.*, 2015; Watts *et al.*, 2015). The Net Zero commitment will see a significant turnover in current thermal plants; thus, it is important to assess the suitability of locations and the water dependence of Net Zero compliant plants in light of future constraints on water availability.

#### 4.10.1 Current and future level of risk (I9)

##### 4.10.1.1. Current risk (I9)

Although vulnerable to reduced water availability, to date there have been no significant interruptions to inland thermoelectric generation reported.

##### 4.10.1.2. Future risk (I9)

###### 4.10.1.2.1. UK-wide

Under climate changes projected by five CMIP5 models, a reduction in usable thermal power capacity in the UK of between 5 and 15% is projected by the 2050s on a pathway to approximately 2°C global warming by 2100<sup>14</sup> and between 10 and 15% or more (depending on location) on a pathway to approximately 4°C global warming by 2100<sup>15</sup>, due to changes in freshwater water

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<sup>14</sup> Based on five CMIP5 climate models in ISIMIP, with projections with the RCP2.6 concentration pathway approximately consistent with 2°C global warming by 2100

<sup>15</sup> ISIMIP, with the central estimate of the CMIP5 projections with the RCP8.5 concentration pathway being in the upper part of the range of the CCRA3 scenario of approximately 4°C global warming at end of century.

availability and water temperatures based on existing plant locations (van Vliet *et al.*, 2016). The magnitudes are supported by Tobin *et al.* (2019) who estimate a reduction in the usable capacity of UK thermoelectric plants reliant on river water of 8% with 2°C global warming and 14% at 3°C global warming, assuming no other changes. While these studies assessed impacts of existing thermal plants, the future vulnerability of energy generation due to reduced water availability caused by both drought and restrictions due to water temperature increases is dependent on how the UK's energy supply changes, while conventional thermal generation will reduce in order to deliver carbon reduction commitments, biomass and gas coupled with carbon capture and storage (CCS) technology, nuclear and hydrogen may play an important role in delivering Net Zero. The UK's Net Zero report (CCC, 2019a) outlines a future with approximately 190 TWh of generation from gas and biomass coupled with CCS by 2050, together with an increase in the use of hydrogen and biofuels. In addition to the requirements for water in thermal generation, electrolysis, carbon capture and storage (including with hydrogen generation) and biofuel production all require water, with the potential to increase the UK's energy systems' vulnerability to reduced water availability (see risk I9).

#### 4.10.1.2.2. England

Within England there is concern that a future deficit of water will compromise the UK's current energy policy to meet an increasing demand for electricity using biomass and gas with CCS (Murrant *et al.*, 2017a). Studies assessing future freshwater availability and a range of future generation scenarios conclude that there could be restrictions in certain areas, particularly around the Thames and Trent Basins and Yorkshire Ouse by 2030 (Byers *et al.*, 2014; Murrant *et al.*, 2017a; 2017b; Konadu and Fenner, 2017). Their analyses conclude that new thermal plants would be better placed on the coast and use sea water as a coolant. Konadu and Fenner (2017) used water availability from CCRA2 data, based on UKCP09, while Murrant *et al.* (2017a) used Environment Agency Data based on UKCP09. The impacts of more recent projections of water availability using UKCP18 have not been used to update this analysis, however it would be anticipated that these projections would confirm the results, or potentially bring forward the date when they may occur. For existing combined cycle gas turbine (CCGT) and conventional plants that remain operating within the Trent Basin and Yorkshire Ouse, there is a risk that by 2030 their output is restricted and their locations become unsuited for uses requiring significant amounts of freshwater (Byers *et al.*, 2014; Murrant *et al.*, 2017a; 2017b; Konadu and Fenner, 2017). An assessment of the system electricity prices attributable to disruption to the supply from thermal plants due to restricted water availability caused by climate change estimates that in the period 2020-2049, costs would be in the region of £93 million and in 2070–2099, £129 million a year, using a large ensemble of the HadAM3P global climate model with RCP8.5 (Byers *et al.*, 2020). Impacts in a pathway to 4°C global warming at the end of the century would be expected to be slightly smaller than for this RCP8.5 projection.

#### 4.10.1.2.3. Northern Ireland, Scotland and Wales

No studies specific to Northern Ireland, Scotland or Wales were found, likely owing to their large thermal power generation being located in coastal areas. Projections by HR Wallingford (2020) of future catchment water availability suggest there could be reductions in catchment water availability by mid-century in some catchments of Northern Ireland, Scotland and South East Wales under a pathway to 2°C global warming by 2100. This would have implications for the siting of any future

thermal generation plants.

#### 4.10.1.3 Lock-in and thresholds (I9)

There is potential for lock-in depending on the future mix of electricity supply technology and siting of thermal power stations and other water intensive activities. The use of carbon capture and storage is highlighted by Byers *et al.* (2014) and Konadu *et al.* (2015) as particularly water intensive. The level of deployment and its siting is therefore important to plan. The CCC (2019b) include both gas and bioenergy-CCS in their pathways to Net Zero as well as nuclear. If these were sited in existing locations where there are likely to be restrictions on freshwater availability due to climate change, the affected plant would be locked-in to these potential future constraints (i.e. the risk of stranded assets). However, for CCS, the CCC (2019a) note that access to CO<sub>2</sub> storage will constrain siting, which excludes Northern Ireland and Wales but highlights Scotland as having the most potential. The locations proposed would likely lie on the coasts of Scotland and England rather than relying upon freshwater. Including an assessment of the future demand for and availability of freshwater in planning considerations would avoid this potential for lock-in.

Thermal electric plants are designed to operate within specific thresholds of water availability and temperature, beyond these limits output is reduced or stopped. There are also limits on the temperature at which water can be discharged back into the aquatic environment, which can restrict future cooling water use.

In addition to the impacts of climate change on freshwater water availability, the effects on the temperature of river, estuarine and marine waters are also relevant to thermal power stations. An increase in water temperature reduces the efficiency of cooling, and water used for cooling is returned to the environment at a higher temperature, potentially >10°C above ambient (Garcia *et al.*, 2016). An increase in average water temperature due to climate change further exacerbates the effects of returned cooling water on the aquatic environment. This could in turn result in some power stations being unable to abstract during periods when water temperature is high because of potential environmental damage if it were to be returned to the aquatic environment, in addition to periods when there is insufficient water available in a catchment.

#### 4.10.1.4 Cross-cutting risks and inter-dependencies (I9)

There are a range of associated interacting risks. Failure to provide a robust means of power has the potential to cascade across the infrastructure sector impacting people, the built environment, business and industry. This was highlighted by the Interacting Risks project, which found the power supply had the highest number of knock-on interacting impacts (WSP, 2020).

Future freshwater requirements from the energy sector are also likely to compete with other users such as agriculture and public water supplies (Risk H10 and I9) as well as safe water levels required for the flora and fauna living within the catchment. Low summer rainfall, increased water temperatures during extreme summer temperatures and droughts can all lead to cooling water capacity being reduced (WSP., 2020).

The risks associated from the use of freshwater for thermal generation also interact with aquatic ecology. When water (freshwater, estuarine or marine) temperatures are raised the temperature at which water is discharged back into the environment is raised further, such elevated output temperatures have an effect on aquatic life and potentially a detrimental effect on reliant bird populations who are unable to adapt their diets (Garcia *et al.*, 2016). Furthermore, elevated water temperatures can enhance biological growth which could block the water intake (ETI, 2018d).

#### 4.10.1.5 Implications of Net Zero (I9)

To deliver Net Zero, a new generation of electricity power options is likely. This will increase the turnover of current thermal plants, but create a stock of new energy technology associated with carbon capture and storage, hydrogen, nuclear (including small modular reactors (SMRs)) biomass and biofuel production, and thus change the nature of these risks as compared to the present. This evolution in supply could potentially increase risk from low water supply if the technologies that are favoured have high water demand. Current CCGTs with closed loop wet tower cooling require abstraction of 0.97 l/kWh and consume 0.78 l/kWh, rising to 1.92 and 1.49 l/kWh with CCS (Byers *et al.*, 2014). Assessments of the full water demand of alternative scenarios consistent with net zero have not been identified (although this work is being undertaken by Energy UK), however, water requirements for hydrogen are given here as an example. A potential future demand of 270 TWh hydrogen could be produced by electrolysis, gas or biomass reformation/gasification coupled with CCS (CCC, 2018c). For hydrogen produced by electrolysis, 0.5 litres of potable water is required per kWh of hydrogen and for gas reforming or gasification require 0.1-0.3 litres non-potable water per kWh and for cooling an additional 0.1 litres (cooling tower) – 30 litres (sea water) (CCC, 2018c). If all hydrogen were provided by electrolysis, 135,000ML of potable water would be required annually. The CCC (2019a) scenarios suggest the majority of the hydrogen requirements in the UK would be provided through gas reforming with CCS, with the use of electrolyzers particularly suited for vehicle refuelling stations due to their size and modular construction. However, other analyses have highlighted the potential for electrolyzers to be deployed faster than CCS technologies (Offshore Renewable Energy Catapult 2020). Related to this, the issues of water could make the Net Zero target more difficult to achieve, in that it could constrain the location of plants or require siting in certain areas (e.g. coasts).

#### 4.10.1.6 Inequalities (I9)

The proposed relocation of infrastructure to the coast in future scenarios (Murrant *et al.*, 2017a; 2017b) does result in some inequalities where local communities in the locations affected share both the benefits and negative impacts of new developments and their eventual closure.

#### 4.10.1.7 Magnitude scores (I9)

Current risk is Low for England, Scotland, Wales and Northern Ireland (Table 4.34). Only England currently has thermal plant greater than 65MW capacity reliant upon freshwater. Assuming current patterns of development and technology remain, England is therefore more exposed to this risk than Scotland, Wales and Northern Ireland. On this basis the future risk is Medium for England in the 2050s under pathways to 2°C and 4°C global warming at the end of the century (Table 4.34), due to

the magnitude of the losses to operators from van Vliet *et al.* (2016) and impact on electricity prices from Byers *et al.* (2020). It is assessed as low for Scotland, Wales and Northern Ireland based on their current exposure. As noted above, changes to the energy mix introduced by Net Zero policy could potentially increase this risk if the technologies that are favoured have high water demand; future water availability should be considered in selecting sites for these technologies.

**Table 4.34** Magnitude scores for risks to energy generation from reduced water availability

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Low  (Medium confidence)	Medium  (Medium confidence)	Medium  (Low confidence)	Medium  (Medium confidence)	High  (Low confidence)
<b>Northern Ireland</b>	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)
<b>Scotland</b>	Low  (medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)
<b>Wales</b>	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)

#### 4.10.2 The extent to which current adaptation will manage the risk (I9)

##### 4.10.2.1 Effects of current adaptation policy and commitments on current and future risks (I9)

###### 4.10.2.1.1 England and Wales

The National Planning Policy Statements in England require the latest climate projections to be taken into account when major new thermal energy infrastructure projects are developed. Plans must give specific reference to the consideration of the increased risk of drought restricting cooling water and the effects of higher water temperatures for fossil fuel plants (DECC, 2011a; 2011b), and the resilience of biomass and Energy from Waste plants to the increased risk of droughts affecting river flow (noting biomass plants are more likely to be proposed for coastal and estuarine sites) (DECC, 2011b). However, it's unclear whether risks are being managed for new smaller infrastructure projects (CCC, 2019). In Wales, Technical Advice Notes include considerations on climate change for developers and are incorporated into Local Development Plans. Currently National Planning Policy



Statements do not provide specific guidance on hydrogen and large-scale biofuel production (whereas their combustion is covered by DECC (2011c)). This gap may be partially addressed through the new abstraction licensing regimes planned by Defra and the Welsh Government; however, these are not yet implemented (Defra, 2019b). The water used by existing thermal power generators is licensed by the relevant environmental regulator and will be subject to proposed water abstraction reforms in England and Wales. Currently abstraction licensing is managed by the Environment Agency and Natural Resources Wales. In England the recently established National Framework for Water Resources brings together regional groups including water companies and other major water users including power station operators to produce long term water resource plans to enhance the resilience of the region's water use to future uncertainties including climate impacts of drought and flood. Their first collective plans are due to be published in September 2023.

#### 4.10.2.1.2 Northern Ireland

In Northern Ireland, the Strategic Planning Policy Statement states the planning system should help adapt to climate change through avoiding development in sites vulnerable to climate impacts. Currently abstraction licensing is managed by NIEA. While water should remain abundant for the existing sites located on the coast and near major estuaries, if new plants reliant on freshwater were to be built, their operations could become constrained if freshwater availability falls.

#### 4.10.2.1.3 Scotland

In Scotland, the National Planning Framework sets out an ambition for new national developments to adapt to climate change, and major new developments of thermal power stations >300MW, nuclear and CCS sites to assess their vulnerability to climate change as part of the EIA under the Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2017. Currently abstraction licensing is managed by SEPA. While water should remain abundant for those sites located on the coast and near major estuaries, any built inland and reliant on freshwater may find their operations become constrained if freshwater availability reduces, depending on where in Scotland they are sited.

#### 4.10.2.2 Effects of non-government adaptation (I9)

Energy UK report adaptation plans on behalf of the sector under the Government's Adaptation Reporting Power (ARP). In their submission to ARP Round 2 in 2015, Energy UK highlighted the lack of probabilistic data on future river flows required to quantify risks of freshwater restrictions. As such it is not clear whether the progress reported in adapting to this risk is consistent with future freshwater availability projections, e.g. from HR Wallingford (2020). Third round risk assessments are not yet available to assess progress. Any risks to the energy system may be compensated by other forms of generation with price implications for electricity outlined by Byers *et al.* (2020). Individual sites would need to manage their risks to the financial losses incurred by any future abstraction restrictions. The water requirements of future energy infrastructure, particularly hydrogen and biofuels, require further consideration.

#### 4.10.2.3. Is the risk being managed? What are the barriers preventing adaptation to the risk? (I9)

Based on the evidence available, current and announced adaptation is expected to partially manage this risk as plans exist in the UK that consider the risks of water scarcity in the future for new developments. However, while the National Framework for Water Resources in England has been established, the group are yet to produce a risk management strategy for existing thermal plant in England. Furthermore, more analysis is needed for hydrogen and biofuel production to understand their risks. An assessment of progress of adaptation measures by energy providers has not been possible as the third round of Adaptation Reporting Power reports have not yet been submitted.

#### 4.10.2.4 Adaptation scores (I9)

<b>Table 4.35 Adaptation scores for risks to energy generation from reduced water availability</b>			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Medium confidence)	Yes (Medium confidence)	Yes (Medium confidence)	Yes (Medium confidence)

#### 4.10.3 Benefits of further adaptation action in the next five years (I9)

##### 4.10.3.1 Additional planned adaptation that would address the adaptation shortfall (I9)

With respect to guiding new small plants which fall under the major infrastructure project thresholds and those already built on inland sites, further actions are warranted given abstraction reforms remain to be implemented in England and Wales, which, together with climate projections for the future water resources available in different catchment areas (Sayers *et al.*, 2020), could guide new infrastructure siting and cooling technology choices. The evidence for risks to energy generation due to higher water temperatures and/or reduced river flows should be kept under review, with long-term monitoring of risk levels and adaptation activity as advised in CCRA2, with additional consideration of how an expansion in hydrogen and biofuel production in the UK would affect vulnerability to reduced water availability.

##### 4.10.3.2 Indicative costs and benefits of additional adaptation (I9)

The costs of further monitoring, and some strategic analysis to look at water related risks (water demand and flooding) for Net Zero generation, are low-regret options and would have clear benefits through the information provided.

For existing thermal plants, there are low regret adaptation options centred on monitoring of risk levels, including early warning and subsequent emergency management during extremes. In other European countries, where these risks have already materialised, adaptation options have focused on demand management and there is some analysis (Perrels *et al.*, 2015) of the economic benefits of demand management options (for industry) and the potential use of smart grids to help manage

non-essential energy use during these events; these might provide options should risks increase in the UK. There are also studies that look at the economic benefits of alternative cooling systems (Després and Adamovic, 2020), which find high benefits, but these tend to be focused on nuclear with river water abstraction (which is not relevant in the UK) or thermal plant (which are being phased out under Net Zero), however these technologies are suitable for biomass and CCS sites.

For the new mix of energy generation for Net Zero, and especially for biofuel, biomass, CCS and hydrogen, the most obvious no regret option is for further analysis of the possible risks with respect to water demand of new generation plant, the number required, and the linkages with Risk I8 on water supply. These factors could lead to important adaptation options around siting and technology options, and at the very least, the cost implications for any water use under a changing climate.

#### 4.10.3.3 Overall urgency scores (I9)

Further Investigation is required in England to understand the extent of future risk to energy generation from reduced water availability in the context of wider demands for freshwater. Updated projections indicate that England is most vulnerable to water supply shortages in future and the impact of this on energy generation is unknown, particularly in the context of an uncertain future energy mix due to Net Zero policy. Scotland, Northern Ireland and Wales have been scored as a Watching Brief, as they have no (Wales and Northern Ireland) or few (Scotland) major thermal plants sited inland and are therefore deemed to have a Low magnitude current and future risk. However, it will be important for climate impacts on freshwater availability to be considered when siting new water dependent energy generators.

**Table 4.36** Urgency scores for risks to energy generation from reduced water availability

Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further Investigation	Watching Brief	Watching Brief	Watching Brief
Confidence	Medium	Medium	Medium	Medium

#### 4.10.4 Looking ahead (I9)

Catchment level assessments of the long-term sustainability of existing thermal plants, together with the provision of updated advice on the suitability of catchments for future projects, could now be delivered with the use of Sayers *et al.* (2020). In England, this work should fall within the remit of the newly established Regional Water Resources Groups. A framework for regular re-assessment as climate and socioeconomic conditions change would enable users to gain confidence when making long term investments in this area. Assessments of the water needs for Net Zero energy portfolios are also required.

## 4.11. Risks to energy from high and low temperatures, high winds and lightning (I10)

The risks within this descriptor are broken down by climate hazard. In summary, there has been little evidence published since CCRA2 that provides additional information on the magnitude of existing or future risks to the energy sector from high and low temperatures, wind or lightning. However, further evidence on the effects of climate change on wind and lightning conclude the effects are uncertain (Clark *et al.*, 2017; Finney *et al.*, 2018; Fung *et al.*, 2018). The future risks related to the energy sector are also influenced by the future profile of energy demand and supply together with the resilience of society and the economy to constraints on or interruptions to supply. Differing generation and supply technologies have their own profile of vulnerability to weather and climate and therefore the balance of these technologies in future will influence the profile of the energy supply's vulnerability to climate change (Bloomfield *et al.*, 2018). Furthermore, Fu *et al.* (2018) conclude that infrastructure policies strongly shape the long-term spatial configuration of electricity networks and that this has profound impacts on their resilience. Current and future magnitude are assessed as high for the four countries. Urgency is scored as 'further investigation' required.

### 4.11.1 Current and future level of risk (I10)

#### 4.11.1.1. Current risk (I10)

Note: It has not been possible to split the evidence by UK country for current risk.

##### 4.11.1.1.1. UK-wide

##### 4.11.1.1.1.1 High and low temperatures (current risk)

Temperatures affect the energy sector through a variety of different mechanisms. Above thresholds (specific to individual components of the energy system) high temperatures can (i) reduce the amount of electricity generation from thermal generators and the efficiency of photovoltaic cells; (ii) reduce the amount of power which can be transmitted and distributed; (iii) cause line sag; and (iv) affect the running of gas compressor stations, while accompanying solar heat (arising typically under conditions of high temperature and low wind) can also cause faults on the electricity network (McColl *et al.*, 2012; National Grid Gas, 2016; CCRA2, 2017). Studies on the impacts of lower temperatures on the energy sector are generally related to the coincident effects of snow, sleet and ice, which are associated with line faults (McColl *et al.*, 2012). While the interactions of high and low temperatures on energy are well understood, evidence that climate change is having an impact currently is less clear.

The ETI (2018a) highlight potential hazards associated with current temperatures in the UK including exports being cut to serve domestic energy demand, price surges, decreased efficiency of thermal conversion, decreased capacity of transmission lines to convey energy, and excessive sag of transmission lines. These risks affect both the supply of electricity and its transmission and distribution. These risks are currently managed by the network operators across the UK.

Temperature is one of the major drivers of energy demand in the UK, notably for winter heating and increasingly for summer cooling (in homes, business and industry). Changes in temperatures affect the temporal and seasonal profile of energy demand, with milder winters on average contributing to lower winter average demand, and hotter summers increasing demand from air conditioning (Thornton *et al.*, 2016; 2017). These effects are discussed in Risk H6 in Chapter 5 (Kovats and Brisley, 2021) and are not included in this risk. Current magnitude is given as low with low confidence (Table 4.37).

#### 4.11.1.1.1.2 High winds (current risk)

ETI (2018b) state the major impacts of wind for energy infrastructure arise from damage caused by wind-blown debris and fallen trees, disruption to transport (relevant for staff accessing critical energy infrastructure locations), reduction in wind power due to low wind speeds and personal safety risks for staff (e.g. due to wind chill during periods of cold weather affecting outdoor workers), and injuries/fatalities from wind-blown debris and fallen trees. In addition, high wind speeds can reduce output from wind farms if speeds are above their safety cut-offs ( $25 \text{ ms}^{-1}$ ) and wildfires in the US have been attributed to winds causing nearby tree branches to touch power lines or as a result of power lines being blown down onto dry vegetation (W. Atkinson, 2018, Electrical Conductor Magazine cited in Gerlak *et al.* (2018)).

The resilience of the power system, or components thereof, to wind has also been explored using a fragility-modelling approach (e.g. Panteli *et al.*, 2017, Dunn *et al.*, 2018, Trakas *et al.*, 2019). When used in a meteorological context, fragility curves describe the impact on a system that results from a meteorological hazard. They are typically presented as failure probability (or simply the number of failures) as a function of a specified hazard, such as wind speed. The resulting curves have a characteristic form, with low fault numbers / failure probabilities at low wind speed, and a rapid rise in fault numbers / failure probabilities when particular wind speed thresholds (which vary depending on the assets being analysed) are exceeded. Here, the impacts of wind speed on energy are understood but there is less evidence that climate change is currently having an impact, hence low confidence in this aspect. Current magnitude is given as high with low confidence (Table 4.37).

#### 4.11.1.1.1.3 Lightning (current risk)

The ETI (2018c) characterise the major impacts of lightning for energy infrastructure as physical damage, fire, power surge, and shock wave. In addition, wind turbines can enhance their own vulnerability to lightning, as their rotating blades can themselves trigger lightning (Montanya *et al.*, 2014, cited in Yair (2018)).

A report by National Grid to Ofgem (2019) detailed the significant and widespread power cut that affected the UK on 9<sup>th</sup> August 2019 following a lightning strike. Over a million electricity customers were affected, but there were wide-ranging additional impacts. Certain classes of electric trains shut down in SE England as their internal protection systems were triggered, causing unpleasant and potentially hazardous conditions for those on board and delaying other services. A subsequent report (Energy Emergencies Executive Committee: E3C, 2020) presented additional detail, including reporting of the societal impacts in the transport, health, water and wider energy sector. A total of

371 trains were cancelled, 220 part-cancelled and 873 delayed on the 9<sup>th</sup> and the morning of the 10<sup>th</sup> of August. There were interruptions to rail signalling and traction. Four hospitals and two airports were affected by the outage. An oil refinery and a chemical manufacturing plant were disconnected by their internal safety systems in response to the power disruption; both plants shut down operations but it took weeks for operations at the refinery to resume fully.

Lightning was found to be a factor in the power cut: *“Two almost simultaneous unexpected power losses at Hornsea and Little Barford occurred independently of one another – but each associated with the lightning strike. As generation would not be expected to trip off or de-load in response to a lightning strike, this appears to represent an extremely rare and unexpected event.”* (Ofgem, 2019).

Despite this being an unusual event, affecting infrastructure that is normally relatively resilient to lightning, it demonstrates the relevance of interdependencies for infrastructure, and has resulted in investigations as to why the interdependent assets/systems reacted to the power disruption as they did (E3C, 2020).

Population and urbanisation trends were identified by Yair (2018) as drivers of change in global lightning risk (note that such changes in risk would be linked to changes in exposure and vulnerability, rather than hazard). In particular, the potential for cities themselves to affect thunderstorm characteristics and thus potential lightning hazard was noted (e.g. the link between the contribution of aerosol (typically pollutant) material from the cities and lightning density). However, all the studies cited referred to cities in locations other than the UK. If this observation did hold for the UK, energy infrastructure in urban areas and wind turbines could be deemed to have a more elevated risk from lightning than may be otherwise expected. Current magnitude is given as high with low confidence (Table 4.37).

**Table 4.37.** UK-wide magnitude scores for current risks to energy from high and low temperatures, high winds and lightning (UK)

	Present day/current risk
Risks to energy from high and low temperatures	Low (Low confidence)
Risks to energy from high winds	High (Low confidence)
Risks to energy from lightning	High (Low confidence)
<b>Overall magnitude score</b>	High (Low confidence)

#### 4.11.1.2. Future risk (I9)

##### 4.11.1.2.1. UK-wide

##### 4.11.1.2.1.1 High and low temperatures (Future risk)

Since CCRA2, the UKCP18 projections for temperature changes have been published (Lowe *et al.*, 2018). Over land, the projected general trends of climate changes in the 21<sup>st</sup> century are similar to UKCP09, with a move towards warmer, wetter winters and hotter, drier summers. The probabilistic projections show more warming is projected in the summer than in the winter. In summer there is a

pronounced north/south contrast, with greater increases in maximum summer temperatures over south-east England compared to northern Scotland. Furthermore, considerations of the impacts of climate change on energy demand and thus on planning energy infrastructure also need to consider cold winters still occurring in addition to warmer winters and hotter summers.

Hanlon *et al.* (2021) calculated various impact metrics for the UK and its constituent countries, under different future levels of global warming from 1.5–4°C, using UKCP18. These metrics are all derived from meteorological parameters and thus are hazard-, rather than risk-, focused. Metrics potentially relevant for high-temperature energy risks included annual numbers of summer days (daily  $T_{max} > 25^{\circ}\text{C}$ ), tropical nights (daily  $T_{min} > 20^{\circ}\text{C}$ ), and cooling degree days (CDD, an indication of energy demand for cooling). Metrics potentially relevant for low-temperature energy risks included annual numbers of frost days (daily  $T_{min} < 0^{\circ}\text{C}$ ), icing days (daily  $T_{max} < 0^{\circ}\text{C}$ ), and heating degree days (HDD, an indication of energy demand for heating). Annual numbers of frost days, icing days and HDD are all projected to decrease with increasing global warming level, with summer days and CDD projected to increase. Annual numbers of tropical nights are small or zero at present but are projected to increase. The projected decreases in HDD were similar across countries but regional variations were found for all other metrics. A country-scale assessment of the high- and low-temperature metrics from Hanlon *et al.* (2021) is presented below.

Other studies have also provided relevant metrics showing similar trends. For example, Guerreiro *et al.* (2018) used climate model simulations under RCP8.5 to study future heatwaves in 571 European cities, 106 of which are in the UK. The temperature metrics provided were percentage of heatwave days and maximum temperature of heatwaves; both metrics are projected to increase, for all the UK cities studied. In addition, in a climate analogue study, Bastin *et al.* (2019) calculated bioclimatic variables for 520 global cities, 8 of which are in the UK, for the present day and for 2050 under RCP4.5. The temperature variables calculated were annual mean temperature, annual temperature range, maximum (minimum) temperature of the warmest (coldest) month, mean diurnal temperature range and mean temperature of the coldest, warmest, wettest, and driest quarters. In almost all cases the values of these temperature variables are projected to increase (increases measured in absolute terms, i.e. future value – present value). Note the contrasting approaches between these two studies and Hanlon *et al.* (2021), who computed the metrics at global warming levels rather than future time horizons.

#### 4.11.1.2.1.1.1 England

Table 4.38 presents projected indices for England from Hanlon *et al.* (2021). The indices considered (all for annual number of days) are frost days (daily minimum temperature  $< 0^{\circ}\text{C}$ ), icing days (daily maximum temperature  $< 0^{\circ}\text{C}$ ), summer days (maximum temperature  $> 25^{\circ}\text{C}$ ), tropical nights (minimum temperature  $> 20^{\circ}\text{C}$ ), heating degree days (HDD, an indication of energy demand for heating) and cooling degree days (CDD, an indication of energy demand for cooling). The largest projected increases in summer days were found in England. England also had the largest projected increases in CDD and the largest projected increases in tropical nights.

**Table 4.38** Change in a range of energy-relevant impact metrics, per global warming level, in England. Ensemble median with the ensemble range in brackets. Frost Days: Daily minimum temperature below 0°C. Icing Days: Daily maximum temperature below 0°C. Summer Days: Daily maximum temperature above 25°C. Tropical Nights: Daily minimum temperature above 20°C. HDD: Heating Degree Days, accumulated daily mean temperature below 15.5°C per day. CDD: Cooling Degree Days, accumulated daily mean temperature above 22°C. Source: Hanlon *et al.* (2021)

Index	Changes in index from mean in 1981–2000: England	
	2°C global warming relative to pre-industrial	4°C global warming relative to pre-industrial
<b>Frost Days (days)</b>	–20 (–26 : –14)	–39 (–43 : –31)
<b>Icing Days (days)</b>	–2 (–2 : –1)	–3 (–3 : –2)
<b>Summer Days (days)</b>	+17 (+13 : +24)	+45 (+37 : +55)
<b>Tropical Nights (days)</b>	0 (0 : 0)	+2 (+1 : +3)
<b>HDD (degree days)</b>	–517 (–557 : –360)	–969 (–1074 : –845)
<b>CDD (degree days)</b>	+37 (+27 : +50)	+114 (+90 : +156)



## 4.11.1.2.1.1.2 Northern Ireland

Increases in Tropical Nights in Northern Ireland are negligible (Table 4.39).

**Table 4.39:** Change in a range of energy-relevant impact metrics, per global warming level, in Northern Ireland. Ensemble median with the ensemble range in brackets. Frost Days: Daily minimum temperature below 0°C. Icing Days: Daily maximum temperature below 0°C. Summer Days: Daily maximum temperature above 25°C. Tropical Nights: Daily minimum temperature above 20°C. HDD: Heating Degree Days, accumulated daily mean temperature below 15.5°C per day. CDD: Cooling Degree Days, accumulated daily mean temperature above 22°C. Source Hanlon *et al.* (2021).

Index	Changes in index from mean in 1981–2000: Northern Ireland	
	2°C global warming relative to 1850-1900	4°C global warming relative to 1850-1900
<b>Frost Days (days)</b>	–21 (–30 : –12)	–37 (–42 : –30)
<b>Icing Days (days)</b>	0 (0 : 0)	–1 (–1 : –1)
<b>Summer Days (days)</b>	+5 (+3 : +6)	+16 (+13 : +21)
<b>Tropical Nights (days)</b>	0 (0 : 0)	0 (0 : 0)
<b>HDD (degree days)</b>	–467 (–512 : –344)	–902 (–1002 : –763)
<b>CDD (degree days)</b>	+9 (+7 : +12)	+32 (+26 : +46)

## 4.11.1.2.1.1.3 Scotland

The largest projected decreases in Frost Days and Icing Days were found in Scotland (Table 4.40). Increases in Tropical Nights in Scotland are negligible.

**Table 4.40:** Change in a range of energy-relevant impact metrics, per global warming level, in Scotland. Ensemble median with the ensemble range in brackets. Frost Days: Daily minimum temperature below 0°C. Icing Days: Daily maximum temperature below 0°C. Summer Days: Daily maximum temperature above 25°C. Tropical Nights: Daily minimum temperature above 20°C. HDD: Heating Degree Days, accumulated daily mean temperature below 15.5°C per day. CDD: Cooling Degree Days, accumulated daily mean temperature above 22°C. Source Hanlon *et al.* (2021).

Index	Changes in index from mean in 1981–2000: Northern Ireland	
	2°C global warming relative to 1850-1900	4°C global warming relative to 1850-1900
<b>Frost Days (days)</b>	–32 (–42 : –18)	–62 (–67 : –53)
<b>Icing Days (days)</b>	–4 (–4 : –2)	–5 (–5 : –5)
<b>Summer Days (days)</b>	+4 (+3 : +5)	+12 (+10 : +17)
<b>Tropical Nights (days)</b>	0 (0 : 0)	0 (0 : 0)
<b>HDD (degree days)</b>	–528 (–574 : –388)	–1011 (–1113 : –891)
<b>CDD (degree days)</b>	+8 (+6 : +10)	+24 (+19 : +37)

## 4.11.1.2.1.1.4 Wales

Increases in Tropical Nights in Wales are smaller than in England (Table 4.41).

**Table 4.41** Change in a range of energy-relevant impact metrics, per global warming level, in Wales. Ensemble median with the ensemble range in brackets. Frost Days: Daily minimum temperature below 0°C. Icing Days: Daily maximum temperature below 0°C. Summer Days: Daily maximum temperature above 25°C. Tropical Nights: Daily minimum temperature above 20°C. HDD: Heating Degree Days, accumulated daily mean temperature below 15.5°C per day. CDD: Cooling Degree Days, accumulated daily mean temperature above 22°C. Source Hanlon *et al.* (2021).

Index	Changes in index from mean in 1981–2000: Northern Ireland	
	2°C global warming relative to 1850-1900	4°C global warming relative to 1850-1900
<b>Frost Days (days)</b>	–19 (–24 : –13)	–35 (–39 : –30)
<b>Icing Days (days)</b>	–2 (–2 : –1)	–3 (–3 : –2)
<b>Summer Days (days)</b>	+12 (+9 : +16)	+31 (+26 : +41)
<b>Tropical Nights (days)</b>	0 (0 : 0)	+2 (+1 : +2)
<b>HDD (degree days)</b>	–505 (–556 : –363)	–972 (–1080 : –852)
<b>CDD (degree days)</b>	+23 (+18 : +31)	+73 (+61 : +108)

The effect of the projected changes to these metrics on the UK energy sector would be variable. Projected decreases in frost days and icing days could reduce the risk to the electricity networks from faults related to frost and ice. Projected increases in tropical nights could also indicate increased cooling demand, as overnight there would be reduced respite from warm conditions. Similarly, projected increases in summer days could also be linked to increased cooling demand, and also to increased stress on temperature-sensitive energy system assets – both network components and supply (see Risk I9). Considering all these phenomena together implies a notable change in future seasonal energy demand profiles and therefore a potential need to change the way in which the energy system is managed. The effects of projected decreases in HDD and reduced winter energy demand, and projected increases in CDD and increased summer energy demand for cooling, are discussed in Chapter 5 in Risk H6 (Kovats and Brisley, 2021).

These statements all assume that change in risk is associated solely with change in hazard, i.e. that

there is no change in exposure or vulnerability. Given the future shape of the energy system is likely to change profoundly in the coming years and decades, in light of the UK's Net Zero aspirations, it is difficult to suggest exactly what changes in exposure or vulnerability could occur and associated magnitude.

In addition to the effects on energy networks, supply side technologies are also affected by changing temperatures (see also I6 and I9). Tobin *et al.* (2018) assessed the impacts of elevated temperatures and wind speed on PV output, stream flow and water temperature (derived from temperature, wind and precipitation climate projections) on thermoelectric power output across Europe as a result of 1.5°C, 2°C and 3°C global warming relative to 1881-1910. They project a reduction in output for PV of between 1-3% and thermoelectric generation of 5-14% relative to 1971-2000. The ramifications of the results are dependent on the future electricity generation mix as well as demand for electricity. The scale of lost revenue associated with a 5-14% reduction in outputs is of medium magnitude. Further evidence quantifying the impacts of projected temperature changes on network performance and generation would better inform an update to the CCRA 2017.

#### 4.11.1.2.1.1 High Winds (future risk)

##### 4.11.1.2.1.1.1 UK-wide

The limited evidence for any trend in average wind speeds due to climate change is still dwarfed by the variability of wind – the climate change 'signal' is very small or negligible compared to the 'noise'. There is no information given about any possible future change in maximum wind speeds, though the limited evidence for a trend in average wind speed suggests evidence for maximum wind speed would be similarly limited. Although the evidence for how climate change will influence wind speed is limited, the anticipated growth in wind power suggests this is an important evidence gap to fill, both in terms of high winds and in light of the evidence reported in Chapter 1 (Slingo, 2021) that summer average wind speeds and thus wind outputs will reduce. A reduction in wind output during summer months could cause concern if electricity demand for air conditioning increases.

A further aspect of relevance for UK energy systems is the 'storm track', the path typically taken by windstorms. Any changes to this storm track could have implications for the frequency and intensity of windstorms, which impact the energy system in terms of its resilience to individual storms and, during runs of windstorms, its ability to recover between events. Murphy *et al.* (2018) show results for the end of the 21st century from the UKCP18 global projections, which suggest:

- In the 15-member HadGEM3 Perturbed Parameter Ensemble (a set of model runs just using the Met Office model), a projected increase in the occurrence of winter storms over the UK and Southern Scandinavia, with reductions to the north and south. This implies a projected strengthening of the southern fork of the winter storm track (the fork passing over the UK and Southern Scandinavia), with a weakening of the core to the north,
- In the CMIP5-13 simulations, (a set of model runs using climate models from other countries) for which storm tracking data are available, a similar pattern to that of the PPE-15, but with the band of increase in the southern fork being weaker.

There is therefore some evidence from UKCP18 that the occurrence of winter storms over the UK could increase, but the magnitude of any such increase differs between sets of climate projections. Bloomfield *et al.* (2016) assessed the weather sensitivity of power systems to climate variability. Four different wind power installation scenarios were examined, corresponding roughly to scenarios of no wind power, the present day, and two future National Grid scenarios for 2025 and 2035. As the amount of wind power installed increases, the total amount of power required from other sources decreases. The reduction is particularly pronounced for power plants expecting to operate as baseload rather than peaking (i.e. for long periods rather than short bursts). Climate variability is found to be important for the future operation of the power system; even the present-day level of wind farm installation has approximately doubled the GB power sector's exposure to interannual climate variability. This raises concerns about the robustness of any power systems planning studies which have used short time series or crude data to represent climate effects.

The main evidence emerging since CCRA2 regarding risks to the energy sector from wind are some increased understanding of the impacts of climate change on wind, reinforcing conclusions drawn from UKCP09 that the climate change signal (in the hazard) is masked by interannual noise (suggesting that current wind-sensitive sectors should focus on planning for interannual variability rather than on any potential climate change trend), the perceived possibility of increased future impacts on certain energy assets and processes from wind, and further detail on the changing vulnerability and/or exposure to wind due to the penetration of wind power supply.

#### 4.11.1.2.1.2 Lightning (future risk)

##### 4.11.1.2.1.2.1 UK-wide

The impact of climate change on lightning strikes is uncertain. Finney *et al.* (2018) compared two different climate model parameterisations of lightning – an existing approach based on cloud-top height and a new approach based on upward cloud ice flux – and found that in scenario of over 5°C global warming<sup>16</sup>, the newer method projected a 15% decrease in global total lightning flash rate of by 2100, which is contrary to the previously-reported global increase in lightning based on the cloud-top height approach. With both methods, however, the projected change in flash rate over the UK was not significant at the 5% level. Clark *et al.* (2017) used eight different lightning parameterisations with data from CAM5 and a range of scenarios to infer future changes in lightning flash rates. They found that the projected changes in lightning were highly sensitive to the choice of parameterisations. Two parameterisations projected a small decrease, but their spatial correlations with observed flash rates and patterns were the lowest, which reduces confidence in their projections. The remaining parameterisations projected varying increases in lightning flash rates.

The changes from CCRA2 regarding risks from lightning provide further information on the effects of climate change on lightning, including the suggestion that lightning could also decrease in future, whereas prior studies had only suggested increases. This suggests an increase in uncertainty in

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<sup>16</sup> Met Office Global Atmosphere 4.0 model driven by RCP8.5 concentrations and sea surface temperature anomalies at 2095-2105 from HadGEM2-ES, the latter model warming by approximately 5.5°C at that time relative to 1861-1890 (Betts *et al.*, 2015)

understanding future impacts compared to CCRA2.

**Table 4.42.** UK-wide magnitude scores for future risks to energy from high and low temperatures, high winds and lightning

	Future risks
Risks to energy from high and low temperatures	Medium (Medium confidence)
Risks to energy from high winds	High (Low confidence)
Risks to energy from lightning	High (Low confidence)
<b>Overall magnitude score</b>	High (Low confidence)

\* Confidence is low in both understanding of the hazard itself and in the vulnerability/exposure of the energy sector to it.

#### 4.11.1.3 Lock-in and thresholds (I10)

The delivery of the Net Zero target will lead to fundamental changes in the energy system. It is likely to lead to a major investment in new energy generation technology, and thus involves a potential risk of lock-in if this infrastructure does not consider future climate change risks. Further evidence on the scale of potential lock-in is required, but it may arise from the climate variables used in the design specifications of new infrastructure commissioned. Different lifetimes of different energy infrastructure asset classes could affect the potential degree of lock-in in different parts of the energy system, as could the future energy mix of the UK (as a whole and for the DAs) – as different policy choices affecting energy mix (particularly the Net Zero ambition) will affect the future prevalence (or not) of particular energy infrastructure assets and thus the exposure and/or vulnerability of the energy system to different hazards. Lock-in has the potential to affect the urgency score for this risk, although it depends on how quickly a future pathway to Net Zero is defined and implemented.

There are currently engineering design thresholds above which equipment will either perform with a lower efficiency (e.g. PV, transmission lines) or cut out (e.g. wind turbines). For assets which are designed according to present-day climate (e.g. for which design specifications contain thresholds which are never exceeded at present) there is potential for issues to arise if standards are not updated, for instance to change asset operating ranges to account for the projected effects of climate change.

#### 4.11.1.4 Cross-cutting risks and inter-dependencies (I10)

In terms of interacting risks, any loss of energy supply, in particular electricity, is likely to lead to cascade failure (see I1) due to the importance of energy supply (Interacting risks project - WSP *et al.* (2020)). This increases the magnitude of risk.

The interacting risks project identified the risks of heatwaves or very hot days leading to power and water demand increases as significant in 2020, 2050 and 2080s (WSP *et al.*, 2020). The risks arising from higher temperatures interact with the increases in energy demand for cooling (Risk H6, Chapter

5: Kovats and Brisley, 2021) and the effects of reduced water availability (Risk I9) which may further restrict the immediate availability of certain sources of electricity generation as well as potentially affecting bioenergy and hydrogen production.

From an international perspective, an increasing number of electrical interconnectors means there is an interdependency with Chapter 7 (Challinor and Benton, 2021).

#### 4.11.1.5 Implications of Net Zero (I10)

The energy system will need to transform if the UK's Net Zero ambitions are to be achieved. Although Net Zero is primarily a mitigation policy, for the energy sector it is important to consider the balance between adaptation and mitigation, as different mitigation strategies aimed at achieving Net Zero will necessitate large changes to the UK's energy mix, and therefore to its sensitivity to weather and climate. Mitigation pathways generally require less reliance on fossil fuels and more reliance on renewables and new technologies.

CCC (2019a) discusses potential approaches to meeting the Government's ambition to reach net-zero greenhouse gas emissions by 2050. The report notes possible ways in which the energy sector could evolve in order to realise the Net Zero target, which will in turn change the vulnerability and exposure of the energy sector to climate change in the relatively short term. For instance, CCC (2019b) suggests that by 2050 with respect to 2017:

- Electricity demand would almost double (despite the fact that it has been falling in recent years) as increases energy efficiencies have offset increasing population and economic activity),
- A ten-fold increase in hydrogen use would need to occur,
- Carbon capture and storage (CCS) would need to be used; it is not yet used at all in the UK.

Wind is clearly both a resource and a risk, and a balance needs to be struck to ensure that new wind generation is resilient to future changes in climate including high and low wind speeds. It is also highlighted that both wind and solar energy are weather-dependent and that even with an expansion of these renewable energy sources, other energy sources will still be needed.

Furthermore, as certain renewable energy generation infrastructure is quite remote, *"additional investments in electricity networks could be required to transport this electricity [to where it is needed]"* (CCC, 2019b)

Energy Systems Catapult (2020) discusses systems modelling conducted explicitly to meet Net Zero. Such modelling considers the whole energy system, rather than individual components thereof. Two scenarios for achieving Net Zero are described, one centralised and one decentralised, with different policies driving different energy mixes and technologies in each case. The report makes the following recommendation for actions during this Parliament, including for the electricity sector:

- Government support for large-scale developments, such as nuclear,
- R&D funding and deployment support for new/emerging technologies key for Net Zero,
- Stimulating efficient demand reduction and/or flexibility,

- Improved market price signals and strengthened network price controls to support decarbonisation.

Such reports suggest approaches for achieving Net Zero and propose actions and timings for these. However, these are only possibilities; it is not yet clear what impact the UK's choices about mitigation will have on the scale of the adaptation challenge. While the UK has good knowledge on the risks of low and high temperature on the existing stock of energy supply technologies, there is less known about new Net Zero technology.

It is also highlighted (see also H6) that climate change will affect energy demand in the UK, reducing winter heating demand, as well as increasing summer cooling demand. This will have implications for the energy system (peak, seasonal and average generation) affecting generation capacity and storage. The impact of higher temperatures on heating and cooling demand has been considered in the preparation of the UK's Sixth Carbon Budget (CCC, 2020a; Box 1.4 and Box 3.8).

#### 4.11.1.6 Inequalities (I10)

Outages remain more likely to customers on radial networks, (e.g. North Wales, South West of England) as well as customers towards the end of distribution networks in rural / upland regions.

#### 4.11.1.7 Magnitude scores (I10)

**Table 4.43** Magnitude scores for risks to energy from high and low temperatures, high winds and lightning.

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)
Northern Ireland	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)
Scotland	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)
Wales	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)



The new information arising since CCRA2 has provided a better understanding of how climate change will alter the wind and lightning risk, whether for the UK or globally. The current impacts of high winds and lightning do currently affect the performance of the energy system, notably the widespread power cut on 9<sup>th</sup> August 2019, in which lightning was implicated. UKCP18 has not changed the message around future projections of wind, however, in which the ‘noise’ of interannual variability is projected to still far outweigh any possible climate change ‘signal’. It is possible that – faced with this seemingly uncertain future information – decision makers might choose to delay actions to reduce wind risk, in favour of actions reducing the risks from other hazards, for which projections seem more robust. This might not be an appropriate course of action, given that the magnitude of the risk is high currently.

There is little new evidence on the impacts of high and low temperatures on the energy sector, and the relative magnitude of the impacts of climate change on the energy sector as a whole, due to high and low temperatures to change the magnitude from CCRA2. This is perhaps because these hazards (and their impact on current UK energy infrastructure) are considered to be relatively well-understood. Although there is evidence on the impacts of high temperatures on different elements of the energy sector (PV, thermoelectric generation, network equipment, demand), the magnitude of the collective impact is not clear, and is dependent on the future evolution of the UK’s energy supply. Additionally, a warming climate is commensurate with the rarer occurrence of cold spells, which itself could have resilience implications in terms of reducing the ‘memory’ of how such events were managed in the past.

There are varying degrees of risk posed by the hazards to energy presented in this section, as well as varying degrees of understanding of the future risk posed in various climate scenarios. It has been demonstrated that weather hazards have the potential to cause high magnitude impacts affecting millions of people (August 2019 power cuts). Individual scores for each hazard are set out in the sections above, however the overall risk is scored at the highest level of risk across all hazards, which is high, with low confidence for present day and for future risk. While understanding of the relationships between the energy sector and temperatures, wind and lightning and the energy sector are good, there is less confidence in the attribution of climate change to the impacts observed to date.

#### 4.11.2 The extent to which current adaptation will manage the risk (I10)

##### 4.11.2.1 Effects of current adaptation policy and commitments adaptation on current and future risks (I10)

The mechanisms which govern adaptation for power generators are discussed in I6 (Hydro), I9 (Thermal) and I11 (Offshore). This includes planning guidance through National Planning Policy Statements (England), Technical Guidance Notes (Wales), National Planning Framework (Scotland) and Strategic Planning Policy Statement (Northern Ireland) together with requirements under Environmental Impact Regulations for climate vulnerability assessments. Existing guidance and statements generally cover larger installations and do not cover all possible climate risks a site may be exposed to (CCC 2019b). For existing operators, they may voluntarily report their plans for adaptation through the Adaptation Reporting Powers process. Both gas and electricity network

companies are incentivised to provide a reliable service during adverse weather and enhance longer term resilience through Ofgem's RIIO price control Framework. The recent RIIO-ED2 for distribution network operators covering the period 2023-28 includes specific reference to the production of a climate resilience strategy and establishment of a climate resilience focus group.

#### 4.11.2.2 Effects of current non-government adaptation on current and future risks (I10)

##### 4.11.2.2.1 UK-wide

Much of the energy sector are invited to produce reports on how current and future climate will affect their organisation and to describe their proposals for adapting to climate change under the Adaptation Reporting Process (ARP) of the Climate Change Act 2008. Electricity generators, transmitters and distributors as well as gas transporters and the regulator Ofgem produce these adaptation reports. The main outcomes of the assessment of temperature impacts, from the latest reports (ARP2) published 2015-2017 (i.e. those which were not published in time to inform the last CCRA), are summarised here. Unfortunately, ARP3 reports are not available at the time of writing to provide an update on more recent activities.

##### 4.11.2.2.1.1 High and low temperatures

National Grid Electricity Transmission (NGET, 2016) ARP2 reported that further information was required in order to assess the longer-term impacts of heat on substation equipment and change existing design standards. In National Grid Gas (NGG, 2016) ARP2 report, the highest-rated impacts related to temperature were effects on control systems / telemetry / ICT for which there are temperature limits for their operation. The maximum operating temperature of the majority of process instrumentation is between 60-80°C; telemetry outstations have a maximum temperature of 55°C and their associated communications infrastructure has a maximum operating temperature of 40°C. National Grid Gas also highlighted weather changes may increase the costs of maintenance, construction, repair and new installations.

NGG's assessment of control systems/telemetry risks includes several temperature thresholds. With future impacts in mind, considering the lowest of the thresholds mentioned (40°C) it is worth noting that Christidis *et al.* (2020) have assessed the likelihood of reaching a temperature threshold of 40°C in the UK at present and by 2100. They found that, statistically, summers which see days above 40 °C have a return time of 100s–1000s of years in the natural climate. This is reduced to 100–300 years in the present climate, and to only about 15 years by 2100 in a scenario reaching approximately 2°C global warming at the end of the century<sup>17</sup>, and 3.5 years in a scenario reaching approximately 4°C at the end of the century<sup>18</sup>. That is, although such temperatures have not been observed in the UK, they could theoretically occur now, and are projected to become more common in future, with the return time being dependent on the emissions pathway followed and the sensitivity of the climate system.

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<sup>17</sup> Central estimate for the CMIP5 ensemble driven by the RCP4.5 concentration pathway, with the multi-model mean reaching 2.4°C global warming in 2081-2100 relative to 1850-1900

<sup>18</sup> Central estimate for the CMIP5 ensemble driven by the RCP8.5 concentration pathway, with the multi-model mean reaching 4.3°C global warming in 2081-2100 relative to 1850-1900

The other thresholds may appear high, but some assets are enclosed, or housed indoors, where the temperatures they experience could be higher than ambient temperatures. It is not clear whether this applies to the assets discussed.

#### 4.11.2.2.1.2 High winds

Analogously to the above discussion for temperature-related impacts, NGET (2016) listed various wind-related impacts, but their own assessment of these rated them as 'green'. For instance, design standards were deemed to account for extreme weather conditions, with substation equipment being designed to a wind speed of  $34 \text{ ms}^{-1}$  (76 mph), and while access to equipment for maintenance and repairs could be constrained during extreme events (including extreme wind), it was deemed unlikely that this would have a prolonged impact on maintenance.

NGG (2016) ARP2 report listed eleven 'amber'-rated impacts related to wind arising from wind-blown debris; safety risk to personnel working on NGG infrastructure, increased wind loading on certain assets (LNG compressor stations and storage facilities), and potential for wind loading to exceed design specifications for some assets.

Projected changes in maximum average wind speeds due to climate change remain uncertain (Lowe *et al.*, 2018). Murphy *et al.* (2018) projected the occurrence of windstorms over the UK to increase in winter, though the magnitude of any such increase is uncertain. Fu *et al.* (2018) find that the electricity system is resilient to windstorms in the current climate, but a 5–10% increase in windstorm intensity and frequency is sufficient to induce a failure to meet demand. A better understanding of projected changes to wind extremes would be useful here (both in terms of frequency of occurrence and magnitude). Based on the uncertainties in maximum wind projections, the need to implement corresponding modifications to the strength design of the overhead electricity lines, poles and pylons would depend on the risk appetite of the regulator; for new infrastructure, there is an opportunity to avoid lock-in due to 'business as usual planning' (see Chapter 2: Watkiss and Betts, 2021) if evidence were to emerge in the future that maximum wind speeds could increase by 5-10% or more. Risks to the distribution system from wind are potentially greater than to transmission infrastructure and may be more resource intensive to manage. Even with the uncertainties around projected future changes to wind, the adverse impacts of high winds in the current climate could warrant a precautionary approach, at least while the evidence base remains inconclusive.

#### 4.11.2.2.1.3 Lightning

NGG (2016) ARP2 report highlighted that while buildings and assets are protected against lightning, if an increase in lightning strikes increased power failures, more standby generators would be considered. NGG also stated that lightning may cause an increase in intermittent loss of telemetry and anticipate that "Business Continuity Management (BCM) plans and plant design provides resilience".

The CCC's 2019 evaluation of the Adaptation Reporting Power reports and wider evidence (CCC,

2019b, 2019c (England and Scotland progress reports)) is that the energy generation, transmission and distribution sector is making relatively good progress in adaptation. However, as noted by the CCC, *“CCRA2 identified risks from wind and lightning as urgent to address for the energy sector....There is a need for better understanding of projected changes in maximum wind speeds and the frequency of such events. If maximum wind speeds were to increase, there would need to be a corresponding modification to the strength design of overhead electricity lines, poles and pylons. It is not clear whether adequate action is being taken to improve resilience to the projected increase in faults to the electricity distribution network caused by lightning strikes.”*

CCC (2019a) recommended that for England, more research is needed on the implications of increased vegetation growth rates on future risks of damage from falling trees during storms. If vegetation growth rates (and the associated risks) were shown to increase in such studies, the potential impact of this could be mitigated by changing vegetation management regimes (e.g. cutting back more often, or ensuring effective monitoring/surveying so that clearances remain sufficient).

#### 4.11.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I10)

Fu *et al.* (2018) presented an integrated approach to assess the resilience of future electricity infrastructure networks to climate hazards. The approach considers different possible ways in which the UK electricity network could evolve depending on policy decisions and changes in supply and demand, and possible changes in the climate hazard (windstorm frequency and/or intensity) and their impact on the network's resilience. Four scenarios were tested (the four combinations of low/high investment cost and centralised/distributed generation) in a simplified model of the power system. The analysis shows that, in this model, infrastructure policies strongly shape the long-term spatial configuration of electricity networks and that this has profound impacts on their resilience. According to the approach, the system is resilient to windstorms in the current climate, but a 5–10% increase in windstorm intensity and frequency is sufficient to induce a failure to meet demand.

Bloomfield *et al.* (2018) studied how the integration of wind power in GB is affecting the overall weather sensitivity of the power system, using three metrics: total annual energy requirement, peak residual load from non-wind sources, and wind power curtailment. The highest-impact weather conditions for the GB power system are different depending on the amount of installed wind power capacity. At the current level of wind power capacity, the total energy generation from non-wind ('traditional') sources is already mostly characterised by the variability in near-surface wind speed, rather than temperature. Without any wind power capacity, the peak residual load from traditional generation is associated with anomalously low 2 m temperatures. With increasing wind capacity, though, the peak residual load tends to be associated with moderately low temperatures and very low wind speeds. This suggests generation adequacy analysis should move away from wind power availability during peak load and towards peak residual load. Demand-limited curtailment events (in which wind power generation is >70% of demand) were associated with low pressure systems north of GB, leading to high wind power production. A major consequence of this study is that the past weather sensitivity of the power system may no longer be an appropriate guide for the future.

In conclusion, there could be an adaptation shortfall related to the implications of temperatures

exceeding 40°C for communications infrastructure resilience, increased vegetation growth rates and the associated future risks of damage from falling trees during high winds and storms, though this remains an uncertain area. There could also be a shortfall regarding resilience to lightning-related risks – however recent studies add uncertainty to the understanding of how climate change will affect lightning hazard. Further investigation of the impacts of climate change on future maximum wind speeds and the seasonal change of wind speeds would enable a better understanding of the extent of any adaptation shortfall associated with wind related impacts.

Several actions in the energy sector are outlined which need to occur (or continue) in the 2020s:

- Continued deployment of baseload and variable low-carbon power,
- Increased electrification of transport and heat,
- Continued improvements in system flexibility,
- Upgrading distribution networks for electrification.

Some of these changes may have positive impacts on the power network from a resilience / adaptation perspective. For instance, upgrading the distribution network has the potential to make it more resilient to weather.

As highlighted in Risk H6 (Chapter 5: Kovats and Brisley, 2021), there is a need for more consideration of the impact of climate change on energy demand, as well as consideration of the potential risks on energy supply technologies. This is important because of the potentially large future demand changes and the large differences in risks across different pathways, i.e. for pathways to 2°C and 4°C global warming by the end of the century.

#### 4.11.2.4 Adaptation scores (I10)

**Table 4.44** Adaptation scores for risks to energy from high and low temperatures, high winds and lightning

Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

#### 4.11.3 Benefits of further adaptation action in the next five years (I10)

There are benefits of additional action in the next five years. For example, further investigation on the implications of increased vegetation growth rates and the future risks of damage from falling trees. The potential for greater use of ‘soft’ adaptation solutions is identified in NGG’s ARP2 report (the specific idea mentioned being changes to working practices). Although organisations are generally already exploring this concept, it is an area where collaboration between companies and between sectors could further facilitate progress in adaptation. There could be benefits in exploring this further through existing collaborative channels.

Metz *et al.* (2016) indicate there are benefits from incorporating climate change information into the decision-making stages regarding the design of new assets and life extension of existing assets. This activity would reduce the potential for lock-in. A watching brief on the evidence regarding future wind speeds could be considered, to be reviewed if evidence suggests an increase in maximum wind speeds of 5% or more are indicated. Further investigation on activities being implemented by the energy sector on existing plans to protect assets from increased lightning strikes is needed to assess whether this should be included as an action here.

There are no regret options involved in better understanding of the potential influence of climate on future energy demand, and thus the Net Zero strategies (see H6), as these influence energy supply.

#### 4.11.3.1 Indicative costs and benefits of additional adaptation (I10)

There is emerging information on the costs and benefits of climate smart design of energy generation including renewables. There is less evidence on the risk levels and potential costs and benefits of climate smart design for the new generation of technologies that will be developed to meet Net Zero, though there are obvious early low regret actions to further investigate these.

There are several hazards and a number of different energy generation technologies within this risk, each of which has particular adaptation responses.

The risk of wind damage to energy supply and transmission infrastructure is one area, and there may be compounding effects from increased vegetation growth. There has been some analysis of these aspects, and the potential increase in vegetation management costs, which can be considered as an impact or an adaptation) (Metroeconomica, 2004), though there are additional options, e.g. wind fences/breaks, circuit breakers, etc. The potential changes in wind regimes and wind power generation are highlighted as a watching brief above: there are technical design as well as operational management options to address potential changes should these emerge.

There is a more general approach for adaptation, with the inclusion of climate risk assessment as part of project design and financial and economic appraisal (see also the Green Book Supplementary Guidance on Accounting for Climate Change, Defra, 2020a). However, there is less evidence on the risk levels and potential costs and benefits of climate smart design for the new generation of technologies that will be developed to meet net zero: an obvious early low regret action is to further investigate these.

#### 4.11.3.3 Overall Urgency scores (I10)

There is a need for further investigation in all four UK countries (Table 4.45), to better understand the future risks to energy from these hazards, particularly high winds and lightning. Better understanding of the implications of increased vegetation growth rates and the future risks of damage from falling trees is also required. Current and announced adaptation actions are not expected to sufficiently manage this risk. The urgency for this risk is assessed with High confidence.

**Table 4.45** Urgency scores for risks to energy from high and low temperatures, high winds and lightning

Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further investigation	Further investigation	Further investigation	Further investigation
Confidence	High	High	High	High

#### 4.11.4 Looking ahead (I10)

More research is needed on the implications of increased vegetation growth rates on future risks of damage from falling trees during storms. The evolution of research into future wind speeds and lightning frequencies hazards will enable a better understanding of the magnitude of these impacts on energy networks and appropriate adaptation responses. Studies such as the NGET assessment which include the likelihood of change as well as its impact are an example of good practice. This risk links to Risks I11, I10 I12 and H6 (Chapter 5; Kovats and Brisley, 2021) which highlight a need for more consideration of the impact of climate change on energy demand, as well as consideration of the potential risks on energy supply technologies which are reliant on weather – particularly those which capture diurnal and seasonal changes in demand and supply. It may be beneficial to increasingly consider the onshore and offshore energy generation, transmission and distribution system together to identify risks on a whole system basis.

### 4.12. Risks to offshore infrastructure from storms and high waves (I11)

Offshore infrastructure includes equipment used by the oil and gas industry, wind, tidal stream and wave energy as well as communications, gas pipelines and power cables on or under the seabed. Their vulnerabilities as a result of storms and high waves include destabilization or degradation of mechanical systems and structures, reduced energy yields and operating periods, loss of integrity of foundations and cabling systems caused by loading and sediment transport across the sea bed, and impeded access for maintenance and inspection activities.

In the future, the risk is allocated as medium magnitude, due in part to the increased vulnerability from the higher reliance on offshore wind for energy supply, since offshore wind capacity is planned to increase from 9 GW currently to 95 GW by 2050, under the CCC's balanced pathway to Net Zero (CCC, 2020b). In addition, a large fleet of oil and gas platforms remains in UK waters, which may be repurposed for carbon sequestration storage and thus remain operational beyond their initially intended lifespan. The length of experience of offshore wind farm operations and resilience is relatively short, due to the limited timespan of this industry to date. Therefore, long term effects are not yet fully understood.

Meanwhile, the confidence in current projections of the effect of climate change on offshore environmental conditions, including wave heights, is low according to the UKCP18 Marine Report

(Palmer *et al.*, 2018). This low confidence in the projected changes in the environment coupled with the short timescale of experience and evidence of offshore wind operations, as well as the rapid growth of this infrastructure and its importance to our energy system, leads to a medium classification of the future magnitude of risk.

Adaptation by the industry can be anticipated based on historic adaptability of the oil industry and the long-term investment in offshore energy infrastructure. The industry adheres to international design standards, which must be evolved as climate impacts on the marine environment become better understood. Current action should be sustained in the next 5 years.

#### 4.12.1 Current and future level of risk (I11)

Note: It has not been possible to split the evidence by UK country for this risk.

##### 4.12.1.1. Current Risk (I11)

###### 4.12.1.1.1. UK-wide (I11)

In UK waters there is extensive infrastructure associated with offshore energy production, including both oil and gas facilities and renewable energy (mainly wind but also tidal stream and wave energy). Oil and gas facilities are in the North Sea, the Irish Sea and west of the Shetland Islands (OGA, 2020). There are ~300 offshore oil and gas platforms, of which ~140 have crew onboard, connected via a network of pipelines (Insite, 2020). This number has been stable since the previous CCRA report in 2017.

Offshore wind farms are primarily found in the southern North Sea and the Irish Sea, and the first farms have recently begun operation in new regions including the Moray Firth and the English Channel (Crown Estate, 2020). The current Crown Estate lease opportunities include zones on the south coast, the Irish Sea and into deeper regions of the North Sea. Currently there are ~3000 offshore wind turbines installed or under construction in UK waters, approximately doubling since the previous CCRA report (Crown Estate, 2018). On the seabed around the UK there is also a network of communications cables that carry telephone and internet traffic to Europe and across the Atlantic.

The oil and gas facilities contain and produce hazardous hydrocarbons and there are typically 100 helicopter flights per day to transfer crew between shore and facilities, with a total of 500,000 crew transfers annually (TSC, 2014). Wind turbines require maintenance and repair, via typically 5 visits per year, when the turbine must be boarded from a vessel in suitably calm conditions. Offshore installation operations are weather restricted and require evaluation of the expected environmental conditions to ensure that there will be adequate weather windows for the planned operations (DNV-OS-H206, 2014). The environmental limits are specified by manufacturers (IEC 61400), and owners manage operations and scheduling; for most current maintenance vessels, a crew transfer to the turbine can take place only when the significant wave height is <1.5 m.

Offshore wind farms currently provide 10% of UK domestic energy consumption (Crown Estate, 2018) and this proportion will continue to rise as new installations come online. The production of



electricity by a wind farm is intermittent due to shutdowns during periods of wind that exceed the design limit, and due to low productivity in calm periods. This leads to a requirement for ‘balancing’ of the electricity grid, particularly when wind farms cease production due to faults, and during calm conditions or excessive wind. This need for balancing is likely to increase in the future.

#### 4.12.1.2. Future Risk (I11)

Marine climate change, including extreme storms, impacts offshore infrastructure. CCRA2 provided a short description of this risk, focusing primarily on qualitative evidence related to the structural integrity of wind turbines and highlighting uncertainty in linking these risks to climate change. For CCRA3 this section has been enlarged, with a wider review of exposure, hazards, vulnerabilities, and risks, linked to more detailed context of the UK’s future offshore infrastructure.

Marine climate change presents a changing hazard to offshore infrastructure. Meteorological and oceanographic conditions that affect the risk to offshore infrastructure from climate change include wind, waves, current and water level.

The marine climate around the UK is summarised in the UKCP18 Marine Report (Palmer *et al.*, 2018). The largest waves offshore of the UK are found off the western coasts, including Cornwall, south-west Wales, and north-west Scotland. These west-facing coasts are dominated by long swell waves that are generated far offshore, in the north Atlantic. The lowest wave heights are found in more enclosed seas, which are sheltered from long swells. In the enclosed seas, such as the Irish Sea and the North Sea, local winds with a short fetch generate short-period waves. The design of offshore infrastructure in these different locations takes account of the different conditions by allowing for the lower loads and altering the structural capacity accordingly. Design codes aim for the same reliability to be achieved, regardless of the location.

The UKCP Marine Report provides UK marine climate projections for the 21<sup>st</sup> century for three different representative concentration path (RCP) climate change scenarios, namely RCP8.5, RCP4.5 and RCP2.6. Projections for the RCP6.0 scenario are not included because the scenario exhibits a similar trend at 2100 to RCP4.5 and has poorer data availability than the other scenarios. In the UKCP18 Marine Projections, the median of the CMIP5-based RCP8.5 projections is in the upper part of the range of the CCRA3 pathway to 4°C global warming by the end of the century (see Chapter 2: Watkiss and Betts, 2021). Key results from UKCP18, for the period 2070-2099, focusing on (i) mean sea level; (ii) wave height; and (iii) wind speed are highlighted, to provide a quantitative basis for review of the offshore infrastructure vulnerabilities.

- a) *Mean Sea Level.* Global mean sea level (GMSL) increased by around 0.2 m from 1901 to 2010, at an average rate of 1.7 mm per year (IPCC, 2013), and this will continue to rise over the 21<sup>st</sup> century under all RCP climate change scenarios. Sea level projections for the UK in UKCP18 are derived from the GMSL projections, and presented in terms of time-mean sea level, which is the baseline water level upon which drivers of sea level extremes, including tides, surges and waves, need to be superimposed.

All RCP scenarios show substantial sea level rise over the 21<sup>st</sup> century. In the south, the

projected rise is on average 0.8 m to 2100 under RCP8.5 scenario, while a lower rise of about 0.5 m and 0.4 m is projected under RCP4.5 and RCP2.6, respectively. For RCP8.5, the range of projections extends up to ~1 m. A lower sea level rise is projected for the north of the UK. The lowest predicted sea level rise is in south-west of Scotland, with a rise of <0.3 m under RCP2.6, and about 0.4 m and 0.5 m under RCP4.5 and RCP8.5 scenarios, respectively. The change in time-mean sea level will dominate changes in the water level extremes during the 21<sup>st</sup> century, with negligible contribution from changes in atmospheric storminess, which is expected to range from about -1 mm/yr to about 0.7 mm/yr, but with overall zero mean.

- b) *Wave height.* Seven CMIP5-based global wave models are used in the UKCP18 Marine Report to provide future changes in mean and mean annual maximum Significant Wave Height (SWH) under RCP8.5. The significant wave height is the mean height (from trough to crest) of the largest one third of waves in a given sea state (other statistical definitions are used, but with minimal practical difference). Results for lower RCPs are not provided. On average, these models project an overall decrease in mean SWH around most of the UK coastline of 10–20% over the 21<sup>st</sup> century. However, it is stated that the projections should be treated with low confidence, due to the variation between different models. Based on the average results, the mean SWH reduces by ~0.2 m to the south west of the UK and Ireland, and by ~0.1 m in the North Sea and the Irish Sea. These changes are in the range 10–20%.

The projected changes in mean annual maximum SWH are in the range +/- 1 m or 20%, but with a more complex spatial pattern than for the mean SWH because they are affected by the passing of individual Atlantic storms. In the central and southern North Sea, a reduction in annual maximum SWH of ~0.5 m is projected. However, an increase by up to ~1 m is projected in the Irish Sea and the northern North Sea. This latter change could be related to a change in sea-ice cover due to global warming, leading to increased fetch for northerly winds in Nordic Seas. There is too much uncertainty among the models to provide a projection for offshore the south west of the UK.

To put these changes in mean and maximum SWH in context, the trough-to-crest height of the probable maximum wave during a storm,  $H_{\max}$ , is a key design parameter, and is typically double the SWH.  $H_{\max}$  rises with increasing latitude from ~20 m offshore Cornwall to ~35 m north of Scotland and west of the Shetland Isles (Santo *et al.*, 2016). The UKCP18 climate projections for RCP 8.5 to 2100 in the Irish Sea and the northern part of the North Sea represent a change in the elevation of the top of this maximum wave of up to ~2 m. This comes from an up to ~1 m rise in sea level combined with half of the 1 m rise in the *trough-to-crest* amplitude of the annual maximum SWH, doubled to represent  $H_{\max}$ . In the central and southern North Sea, the predicted reduction in annual maximum SWH of 0.5 m could compensate for the rise in sea level, leaving the elevation of the annual maximum wave unaffected.

However, these changes are affected on a decadal timescale by the strength of the North Atlantic Oscillation (NAO), which is the fluctuation of the difference between the Icelandic low pressure and Azores high pressure regions. The NAO affects the strength and direction

of westerly storm tracks approaching the UK and alters the  $H_{\max}$  to the west and north of the UK (from Cornwall up to the Shetlands) by typically  $\pm 3$  m over a decadal period (Santo *et al.*, 2016).

- c) *Wind speed.* The mean changes in wind speed predicted by the CMIP5 climate models (Wade *et al.*, 2015) have similar patterns to changes in mean SWH discussed earlier, with a reduction to the west and south west of Ireland, and slight increase to the north of the British Isles. The differences from historical conditions to end-21<sup>st</sup> century RCP8.5 are on the order of 0.5 m/s. Changes in the mean annual maximum wind speed are spatially variable, with changes of the order  $\pm 1.5$  m/s in places (Palmer *et al.*, 2018). Under the H++ scenario, defined as the more extreme climate change scenarios on the margins or outside of the 10<sup>th</sup> to 90<sup>th</sup> percentile range presented in the UKCP09 projections (Murphy *et al.*, 2009), the model projects a 50–80% increase in the days of strong winds over the UK by 2070–2100 compared to the period 1975–2005.

Together, these three effects of climate change create the following vulnerabilities: the stability and degradation of structures and mechanical systems (e.g. turbines), the energy yield and operating window (periods of operation) of turbines and facilities, sediment transport across the seabed, influencing the integrity of foundations of subsea infrastructure and cabling systems, the accessibility of structures for maintenance, inspection and crew transfer, and the operation of ports and coastal infrastructure for maintenance and inspection activities.

#### 4.12.1.2.1 Effect on the stability and degradation of structures and mechanical systems (e.g. turbines)

Offshore infrastructure is designed against limit states that may be controlled by a single extreme load, or by an accumulation of many small loading events, or a combination of both. For example, the stability of a structure is primarily dependent on the largest single load, but prior cycles may weaken it. Fatigue failure of structural or mechanical components, or progressive tilt of the structure, may be controlled by both large (infrequent) and small (frequent) loads, depending on the structural form, the materials and the ground conditions. Small changes in load level can have a large effect on structural life. This is because the number of cycles to fatigue failure depends on the applied stress raised to a high power, typically 5 for high cycle fatigue modes (Bai and Jin, 2015). Consequently, a 10% change in load reduces the structural life by a factor of  $1.1^5 = 1.6$ .

The extreme loads on a structure are typically driven by the largest wave in an extreme storm event. Examples of smaller but more frequent loads are the cycles caused by a wind turbine blade passing the tower or by the waves in rough seas. The maximum single extreme load on a fixed structure is affected by climate change through the severity of the extreme storm event combined with the increase in sea level. As outlined above, the projected rise in the elevation of the crest of the annual maximum storm wave is up to  $\sim 2$  m by 2070–2100 under RCP8.5, from the combined changes in sea level and waves. However, in some regions the effect is projected to be smaller, such as the southern and central North Sea, where the majority of current wind farms are installed.

The corresponding increase in load on platforms and turbine structures can be assessed by

extrapolating existing design approaches. The change may be only a small fraction of the total load but in some situations could be a large step increase. For example, where an ‘air gap’ is allowed beneath a platform so that extreme waves pass through the platform legs but do not impact on the structure, the rise in extreme wave elevation could bring water into contact with the platform. This threshold will cause a sharp rise in the extreme load and structural risk that is disproportionately greater than the rise in the wave crest height. A systemic design change and remediation or mitigation process would be triggered by this threshold, if reached.

Deck structures and access platforms that are not designed to resist direct wave forces are required by design codes to have an adequate air gap from the bottom of the structure to the elevation of the highest wave crest. For example, the DNVGL-ST-0126 design code for offshore wind turbines requires an air gap of at least 20% of the SWH (or 1 m at minimum) with a return period of 50 years.

Strategies to incorporate the effects of climate change into design input parameters for the stability of structures are in their infancy. The concept of considering both ‘start of life’ design inputs and also ‘end of life’ inputs, which are selected allowing for climate change forecasts, is described by Brown *et al.* (2019) using an oil and gas project in the far east as a case study. Comparable published strategies for UK waters have not been found. Some design codes for offshore infrastructure reference climate change when setting out how design values should be selected. For example, the DNVGL-ST-0126 design code for wind turbine support structures states that future changes in sea level should be considered. However, design codes do not prescribe a specific basis for this selection. Meanwhile, the National Policy Statement for Renewable Energy (2011), among its considerations for climate change adaptation, requires that applicants building offshore wind farms “should particularly set out how the proposal would be resilient to storms.”

Finally, failure or damage rates for existing infrastructure, such as wind turbines, are not publicly available. Wind farm reliability studies often rely on old data sets from onshore turbines (e.g. Martin *et al.*, 2016, Dao *et al.*, 2019). There is therefore a data gap on the current failure rates and structural performance, as well as uncertainty about potential future changes in loading and therefore stability and machine degradation.

#### 4.12.1.2.2 Effect on the energy yield and operating window (periods of operation) of turbines

A rise in wind speed leads to increased energy production by wind farms, but this also causes an increase in wear and maintenance requirement and reduces the accessibility for crew vessel transfers. Changes in the wave and wind climate lead to a change in the capacity factor of wind turbines, i.e. the annualised electricity yield relative to their rated capacity. Based on the RCP 6.0 forecast, Hdidouan and Staffel (2017) examined the change in capacity factor for offshore wind around the UK, to 2050 and 2080. They found a small (<1%) change for farms east of England in the North Sea, with small increases in capacity factor moving further north, reaching 5% to the north and west of Scotland. These variations are comparable to the current 1-2% year-on-year variation in capacity factor across the entire UK fleet of wind farms associated with annual variability in storm events and other operational issues (Crown Estate, 2018). Chapter 1 (Slingo, 2021) highlighted recent climate modelling which suggests a reduction in average wind speeds and corresponding power output during summer periods, however this has not been quantified. The seasonal pattern

of power supply has ramifications for network management.

In addition to climate-related changes in average wind speed, a shift in the storm track paths or the strength of the driving forces due to the NAO could lead to a change in the spatial distribution of wind speeds around the country (Cradden *et al.*, 2015). There is some evidence to suggest that the paths of incoming Atlantic storms may change under future climate change scenarios (e.g. Jiang and Perrie, 2007; Woollings *et al.*, 2012; Zappa *et al.*, 2013) although confidence in such projections is low. Cut-in and cut-out wind speeds for wind turbines have remained practically unchanged as the size of devices has evolved over the past decade, with typical values of 3 or 4 m/s and 25 m/s, respectively (Gaertner *et al.*, 2020).

The changes in annual mean SWH due to climate change affect the energy available for harvesting by wave energy devices. Reeve *et al.* (2011) used Cornwall's wave hub facility and a particular Wave Energy Converter (WEC) to provide a case study of the effect of climate change on wave energy yield. Their study examined projected changes for the period 2061 – 2100 for scenarios that reached approximately 3°C and 4°C global warming at the end of the century<sup>19</sup>. Their modelling projected reductions in mean annual yield of 2-3% relative to present day conditions for both scenarios due to a combination of increased downtime and changes in device efficiency with wave steepness. These changes are small relative to the inter-annual changes in yield and also the likely improvements in the power and yield of commercial WEC systems by 2100.

Tidal stream devices, being underwater, are less susceptible to changes in sea level and SWH and are generally located in regions of shallow water.

#### 4.12.1.2.3 Effect of sediment transport across the seabed, and the integrity of subsea infrastructure

Sediment transport can lead to the migration of small ripples or large sand waves across the seafloor, as well as the generation of deep scour holes, 2–3 diameters deep, around the legs of platforms and wind turbines. Sediment transport and scour can affect the stiffness and stability of wind turbines and can damage subsea cables. In UK waters, two wind turbines have been removed from the Robin Rigg farms due to sediment transport causing a loss of foundation support (Smith and Lamont, 2017).

The changes in annual mean and maximum SWH projected by UKCP18 may trigger sediment transport at locations where it does not currently occur, or stabilise sands that are currently mobile in other areas, so there is the potential for unexpected problems associated with sediment transport. Research has been instigated into the hazard of scour in the face of climate change (Arboleda Chavez *et al.*, 2019). However, the future change in risk level to existing and new offshore infrastructure has not been explored in published studies.

Cable failures are a particular criticality for wind farm availability because failure of a single cable can prevent production from a large part or all of a wind farm, as compared to a single turbine failure, which does not affect the other turbines. According to an insurer's analysis, 77% of the losses from a

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<sup>19</sup> SRES B1 and A1B scenarios

global analysis of wind farms are attributable to cable failures (Gulski *et al.*, 2019). A separate analysis identified that approximately 50% of subsea cable failures are attributed to environmental conditions, leading to abrasion or other damage (Dinmohammadi *et al.*, 2019). Therefore, subsea cables are notably exposed to changes in the offshore environment such as scour and sediment transport due to climate change, although currently these risks have not been quantified.

#### 4.12.1.2.4 Effect of the accessibility of structures for maintenance, inspection and crew transfer

The projected reduction in mean SWH across the southern and central North Sea projected by UKCP18 will widen operating windows for vessels and improve accessibility to offshore installations. The availability of a wind farm – i.e. the proportion of time that it is available for power generation – is affected by accessibility when maintenance is required (Brooks *et al.*, 2020). Simulations by Dinwoodie *et al.* (2018) show that although availability can be close to 100% in summer, during winter months the accessibility falls, because of the limited weather windows for vessel access. Their study did not make predictions of the change in accessibility for specific future climate scenarios, but a variation case with 10% lower SWH showed an approximately 10% rise in availability, from typically 75–85% during the winter season.

In the future, autonomous and remote monitoring, and potentially autonomous maintenance, will reduce the influence of accessibility on wind farm availability. Coupled with the expected reduction in mean SWH in the southern and central North Sea, the expected change in accessibility risk of wind farms in this area from climate change is negligible or a reduction.

#### 4.12.1.2.5 Effect of the operation of ports and coastal infrastructure for the maintenance and inspection activity

The operating and maintenance of offshore infrastructure requires transport by boat from coastal ports. Climate change will have an impact on coastlines and ports, and may affect the operation of the port infrastructure associated with maintenance bases.

#### 4.12.1.3 Lock-in and thresholds (I11)

Since offshore infrastructure is designed for a 30 to 40-year life, and the consenting period plus construction is 5 years, then decisions now affect the capacity and resilience of offshore infrastructure and energy supply in 2060.

For example, offshore wind farms in locations where wind and wave loading will be increased by climate change will become more vulnerable and less available. Therefore, although the changes in vulnerability highlighted above are generally small relative to the annual and decadal variability from other effects, the risk is locked-in because adaptation is costly once structures are installed.

Oil and gas infrastructure that is currently reaching the end of production life may form part of a future CCS system. The decision to remove or adapt this infrastructure for CCS will affect whether this opportunity remains.

As wind farms move into deeper water, further from shore, there will be a progressive increase in the proportion of turbines that are supported on floating platforms rather than being fixed to the seabed. Floating wind platforms have different accessibility, availability, and reliability relative to fixed wind, so the risks highlighted above may change in severity as the proportion of offshore wind sited on floating platforms increases. The rate at which floating wind expands will depend on policy as well as technical drivers, including the approach to integrate intermittent renewable energy and energy storage across the UK's grid (Moore *et al.*, 2018). Currently the transition from fixed to floating wind is driven by economic and marine spatial planning drivers, but this threshold may also represent an adaptation that affects climate change resilience.

A further threshold highlighted above is the elimination of the 'air gap' beneath structures by rises in sea level and extreme wave elevation, causing a significant step increase in loads on structures. A systemic programme of remediation or mitigation would be triggered by this threshold.

#### 4.12.1.4 Cross-cutting risks and inter-dependencies (I11)

The high reliance on offshore wind and subsea cables adds vulnerability to the electricity grid and the need for balancing capacity. 'Cut-out' events in storms or due to delayed maintenance caused by inaccessibility in high waves will have a greater impact in the future than they currently do. This creates an interacting risk with the overall energy system, which needs greater resilience when it is more dependent on wind energy (e.g. Bloomfield *et al.*, 2018). This risk may also have international implications due to the increased numbers of electrical interconnectors.

The installation and maintenance operations of offshore infrastructure can only be carried out under restricted environmental conditions and adequate weather windows, at both the infrastructure and the port or shore bases. As discussed earlier, climate change may impact such activities and potentially result in longer downtimes due to limited access to infrastructure during unfavourable environmental conditions. As a result, this creates an interacting risk with the need for energy storage or other back-up sources to support the electricity grid, as it becomes more reliant on offshore wind.

#### 4.12.1.5 Implications of Net Zero (I11)

The UK's fleet of offshore wind turbines is expected to at least double by 2030 reflecting the UK Government aim to reach 40 GW of installed capacity by then. The CCC's balanced pathway to Net Zero by 2050 involves 95 GW of offshore wind capacity by then, and they recommend an aim of 75–140 GW of offshore wind being deployed by 2050 to cover different scenarios. This 95 GW target will require on the order of 10,000 turbines to be operating in UK waters in 2050, occupying 1–2% of the Crown Estate seabed. For this future fleet of ~10,000 turbines, a typical requirement of 5 visits per year to each turbine corresponds to >100 wind turbine boarding's per day, although changing monitoring and maintenance methods may reduce this requirement.

Since the UK's electricity supply will rely more heavily on offshore wind, the requirement for balancing generation and electricity storage will increase, to address the risk associated with supply variability including intermittent cut-out of wind farms. In addition, a larger proportion of UK power

will be supplied via electricity, for example through the electrification of transport. This raises our reliance on the offshore infrastructure of wind farms and subsea cables for balancing transmission of electricity to and from Europe.

The UK's operating offshore oil and gas facilities are likely to decline in number towards 2050, but when a field shuts down there are significant offshore operations associated with decommissioning works, which involve large crewed vessels operating to remove structures and also plug and abandon wells. While oil and gas production is in decline, some of the associated infrastructure will remain in place after decommissioning (RAE, 2013), and may be repurposed for carbon capture and storage infrastructure (Williams *et al.*, 2013).

#### 4.12.1.6 Inequalities (I11)

None identified at present.

The amount of oil and gas infrastructure in UK waters has been stable since the previous CCRA report in 2017, and there is no new evidence to suggest a change in the overall hazard for the present time. Although exposure has slightly increased due to the deployment of new wind farms (currently there are about 3000 offshore wind turbines installed or under construction in UK waters, with recent wind farms in new regions including the Moray Firth and the English Channel), there is no new evidence to suggest a change in the current magnitude of risk since the last CCRA.

The UK Government has put offshore wind at the heart of the national energy future, through the Offshore Wind Sector Deal and the Net Zero roadmap. The quantity of offshore renewable energy infrastructure will therefore increase significantly over the 21<sup>st</sup> century, along with society's reliance on its electricity supply. Owing to this increasing offshore renewable energy infrastructure, and the continued presence of a large fleet of oil and gas platforms that may be repurposed for carbon sequestration and storage, and thus remain operational beyond their initially-intended lifespan, the risk exposure of offshore infrastructure will grow significantly.

The UK has historically relied on offshore infrastructure for energy production through oil and gas, but this has been imported from diverse overseas locations in addition to production in UK waters. By 2050, Net Zero projections indicate approximately 50% of UK electricity will be generated by offshore wind in UK waters (CCC 2020b), so energy security will be strongly dependent on the continued operation of around 10,000 offshore wind turbines – five times more than are currently installed.

Meanwhile, the confidence in current projections of the effect of climate change on offshore environmental conditions is low, according to the UKCP18 Marine Report. Also, the length of experience of offshore wind farm operations and resilience is relatively short, due to the limited timespan of this industry to date. Therefore, long term effects are not yet fully understood.



## 4.12.1.7 Magnitude scores (I11)

The projected consequences of climate change on offshore infrastructure outlined above are generally low, and in some cases represent a reduction in risk. However, the low confidence in the projected changes in the environment coupled with the short timescale of experience and evidence of offshore wind operations as well as the rapid growth of this infrastructure, its vulnerability to changes in environmental conditions, and its importance to our energy system, leads to a Medium classification of the future magnitude of risk.

**Table 4.46.** Magnitudes score for risks to offshore infrastructure from storms and high waves

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Low	Medium	Medium	Medium	Medium
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Low	Medium	Medium	Medium	Medium
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Low	Medium	Medium	Medium	Medium
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Low	Medium	Medium	Medium	Medium
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

## 4.12.2 The extent to which current adaptation will manage the risk (I11)

## 4.12.2.1 Effects of current adaptation policy and commitments and on current and future risks (I11)

## 4.12.2.1.1 UK-wide

Adaptation of offshore infrastructure design and operation to account for the changes described above is taking place via the following two routes, which manage and mitigate the risks.

The design of offshore infrastructure is highly regulated by international standards. These codes have evolved from the oil and gas industry, which is inherently hazardous and has a good framework for assessing and mitigating hazards and risk. These design codes are evolving to include requirements to allow for future effects of climate change in the selection of environmental loads

and other actions on offshore infrastructure. For example, the most recent update of ISO 19900, which is the top-level ISO Standard for offshore structures, introduced a recommendation that changes in design conditions due to climate change be considered (ISO, 2019). Similarly, the design standard that is most widely used by the offshore wind industry, states that sea level rise due to global warming must be included in extreme wave elevation calculations (DNVGL, 2016).

Government and the private sector are both heavily investing in offshore renewable energy industries. The UK government is strongly committed to a successful offshore wind industry, for example through the Offshore Wind Sector Deal (HM Government, 2019b), as Point 1 of the Ten Point Plan for a Green Industrial Revolution (HM Government, 2020b), and through its role in planning and consenting of new projects, overseen by the Crown Estate and the Crown Estate Scotland. Meanwhile, the owners and operators of offshore wind facilities are major organisations with long term commitment and investment in their wind farm projects, each of which represent a multi-billion-pound investment, with the 30 to 40-year horizon.

#### 4.12.2.2 Effects on non-government adaptation (I11)

The oil and gas industry has historically applied adaptation as environmental conditions change or become better understood, leading to revised design assumptions. This process is continuing via the same protocols to accommodate climate change. Examples of these provisions as applied to a particular design cases are presented by Toumi *et al* (2008) and Brown *et al* (2019).

Research and development are unlocking new technologies to support the offshore renewable energy industry, providing potential adaptation routes to mitigate climate change effects. These new technologies include floating offshore wind platforms, robotic and autonomous inspection and maintenance, and tidal turbines and wave energy devices. These technologies offer alternative solutions to develop offshore energy that have different exposures to the effects of climate change. The UK has a world-leading capacity for fundamental and applied research related to offshore energy for renewable energy, legacy oil and gas infrastructure, marine science, and oceanography (e.g. BEIS, 2016, 2017).

#### 4.12.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I11)

As outlined above, offshore energy infrastructure is heavily regulated in design and operation. The stakeholders span government, the private sector and academia, and have the expertise and resources to implement climate-related adaptations in the design and operation of new infrastructure. Meanwhile, new technologies are providing new adaptation pathways to mitigate climate change effects. The offshore renewable energy industry is relatively new and is rapidly growing in scale and moving to new offshore regions. As a result, there is currently a limited evidence base for the current risk levels and vulnerability. If the actions outlined above continue to take place, it is expected that the risk to offshore infrastructure will remain at the current levels or reduce. It is therefore likely that there will be no adaptation shortfall in the next 5 years.

## 4.12.2.4 Adaptation scores (I11)

<b>Table 4.47</b> Adaptation scores for risks to offshore infrastructure from storms and high waves			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Yes (Medium confidence)	Yes (Medium confidence)	Yes (Medium confidence)	Yes (Medium confidence)

## 4.12.3 Benefits of further adaptation action in the next five years (I11)

## 4.12.3.1 Additional planned adaptation that would address the adaptation shortfall (I11)

Adaptations are outlined in Step 1 and include changes to the design loads, extreme wave elevation and accessibility of offshore infrastructure for maintenance and crew transfer. In some regions these changes represent a rise in risk, and in others the net effect may be a reduction (i.e. a reduction in wave height counteracting the rise in sea level). Also, the expected changes in average annual energy production per unit of installed capacity by 2100 are comparable to the existing year-to-year variability. All these forecasts are predicated on the projected effects of climate change on the marine environment, for which there is currently low confidence. Given the anticipated expansion of offshore renewable energy in order to meet Net Zero and current low confidence in marine projections, further investigation into the potential changes in relevant climate metrics including wind and wave heights could better inform design and siting choices.

## 4.12.3.2 Indicative costs and benefits of additional adaptation (I11)

This risk is evaluated as Sustain current action. As with the previous risks, the potential changes in the offshore wind regime and implications for offshore energy infrastructure (notably offshore wind), as well as other offshore risks (e.g. wave regimes), requires periodic review (e.g. Stewart *et al.*, 2014), but there are technical designs for turbines as well as operational management options to address potential changes should these emerge, and a general recommendation on the use of climate risk assessment in new project design and appraisal. Offshore, subsea cable failures are currently the most important failure risk; these can occur from changes in tidal flows (Dinmohammadi *et al.*, 2019) and might warrant further consideration of risks.

## 4.12.3.3 Overall urgency scores (I11)

Based on the assessment of current and future magnitude of impact, as well as the judgement that current and announced actions should maintain or reduce this magnitude, it is assessed that current actions should be sustained. This is assessed with medium confidence. This may need to be reassessed pending developments around Net Zero and the growing importance of offshore infrastructure, especially energy generation from wind.

**Table 4.48** Urgency scores for risks to offshore infrastructure from storms and high waves

Country	England	Northern Ireland	Scotland	Wales
Urgency score	Sustain current action	Sustain current action	Sustain current action	Sustain current action
Confidence	Medium	Medium	Medium	Medium

#### 4.12.4 Looking ahead (I11)

To support the current adaptation activities to further actions are identified:

- Improvement of confidence in projections of the changing marine environment. These projections currently have low confidence and are at a coarse regional scale,
- Improvement of baseline data documenting the performance and reliability of new types of offshore infrastructure, such as offshore wind turbines.

The UKCP18 Marine Report identifies a low confidence level in projections of the future wave climate and wind conditions in offshore regions. These projects also have a coarse regional scale, so offer limited quantitative evidence for local vulnerabilities such as changes in the movement of sand banks or erosion of seabed sediment at particular locations.

The offshore wind industry is undergoing a rapid expansion and there is a limited track record of performance data available for assessing adaptation requirements. As noted previously, the available reliability and failure data is predominantly from smaller onshore wind turbines. For effective adaptation, it will be necessary for the performance of the current and new infrastructure to be monitored and analysed to determine baseline data, which can be used to improve projections of future scenarios. The international element of this risk associated with increased numbers of electrical interconnectors is an area which may benefit from further research.

### 4.13. Risks to transport from high and low temperatures, high winds and lightning (I12)

The current risk magnitude score for transport is medium, with high confidence. For future scenarios, the risk magnitude is high with low confidence. Heat-related rail buckling is identified as a key issue (but note that progress on adaptation in the rail sector is generally well-advanced). The urgency score for the whole UK is 'more action needed' with medium confidence, acknowledging that action will varied between modes and for different climate hazards, with further research also needed where appropriate. Although transport was included in CCRA2, it was combined with the energy and digital sectors and assessed on the basis of hazard (e.g. 'Risks to energy, transport and digital infrastructure from high winds and Lightning'), hence this precludes a direct comparison between assessments.

Assessment of planned and announced adaptation actions within the transport sector indicate that the risk is only being partially managed across the system. Although there are examples of good practice within individual transport modes and emerging activities taking place, the approach to managing climate risks across the transport infrastructure is not comprehensive and is not being undertaken from a mobility/whole-systems perspective.

As well as tackling existing issues such as avoidable uncertainty in basic asset data, reducing climate risks to transport will require the formal assessment of the future electrified transport systems that will be required to meet the UK's Net Zero commitments. This will include the identification and mapping of new interdependencies with the energy sector (electricity generation, transmission and distribution networks) and the digital/ICT sector.

#### 4.13.1 Current and future level of risk (I12)

Note: it has not been possible to split the evidence by UK country for this risk.

##### 4.13.1.1 Current risk (I12)

###### 4.13.1.1.1 UK-wide

###### 4.13.1.1.1.1 Rail (current risk)

Network Rail (2017a) reported that the impact of high temperatures on their network was responsible for over £20 million in compensation payments to Train Operating Companies (TOCs) between 2006 and 2016. Heat can cause rails to buckle, overhead cables to sag, signals to fail and prevent maintenance from being performed (RSSB, 2015). Railway assets tend to demonstrate threshold temperatures, beyond which failures manifest. For example, to maintain seasonal resilience to the average UK climate, Network Rail 'pre-stress' rail to a stress-free temperature (STF) of 27°C. In reality, once the track is laid, this resilience reduces as the ballast moves and settles, meaning STFs can be 3°C lower within a year, hence maintenance (particularly tamping) is essential to maintain resilience.

Network Rail (2015) state that failure rates for most of their railway assets start to increase notably at temperatures as low as 20°C, thereafter increasing more dramatically from 26°C. Although modernisation of certain assets such as overhead cables with auto-tensioning have reduced their vulnerability to heat, RSSB (2015) state that modern signalling is more susceptible to heat due to its dependence on electric and electronic components. Many railway components require further research to determine failure thresholds (Ferranti, 2016).

Ferranti *et al.* (2018) present a notable example of the impact of a heat event on the rail network of Great Britain. The 1<sup>st</sup> of July 2015 saw temperatures as high as 37.5°C (at Heathrow, the record for July at the time). Heat-related incidents on major routes such as London North Eastern (which connects London and Scotland) and at critical nodal points in the network, such as near Manchester Piccadilly, caused major disruption. Across Great Britain, failure and impairment of assets, as well as

emergency speed restrictions, caused 220,000 delay minutes, with all regions experiencing at least double their daily average delay minutes, costing an estimated £16 million to the national economy.

Ferranti *et al.* (2016) looked at the vulnerability of South East England's railway network to heat, particularly how the impact of a given heat event depends on its timing within the onset of the summer season. It was argued that the 'failure harvesting' phenomenon, where at-risk assets fail when they reach a critical temperature for the first time in a given year, can mean the risk profile for rail can sometime reduce during the course of the summer. Hot spots of incident occurrence were observed in urban regions such as London (owing to the concentration of infrastructure and urban heat island effects). Effects on Network Rail signalling were seen to be particularly significant, accounting for 53% of heat-related incident costs and 51% of delays in the South East of England. The conclusions around failure harvesting were borne out with the prolonged heatwave in summer 2018 which caused a 40–50% increase in asset failure rates on hot days compared with those expected on normal days, with hot days earlier in the year (April–June) seeing increases of up to 80%.

Wind accounted for approximately £145 million in compensation payments between Network Rail and TOCs between 2006 and 2016 (Network Rail, 2017a). Of the 37,820 weather related incidents in England between 2006/07 and 2017/18, 31% were attributed to wind and 23% to snow (ADAS, 2019). Wind can disrupt operations by blowing branches, trees and debris onto the line, with 2.5 million trees estimated to be growing alongside the rail network. Fu and Easton (2018) used a logistic regression model to study the contributing factors to wind-related rail incidents for the Anglia Route between 2006 and 2015. The likelihood of an incident was shown to be greatest for north-easterly winds, and decreased by more than 60% for south-westerly winds.

Network Rail (2017a) reported £40 million in compensation payments to TOCs due to the impact of lightning on their network between 2006 and 2016. Lightning can cause damage to electronic equipment, line-side trees and buildings as well as cause line-side fires. As outlined in Risk I11, the damage lightning causes to the electricity transmission and distribution system can have knock-on impacts to the railways, such as the power outages in England and Wales on the 9th of August 2019 (Ofgem, 2020a).

Between 2006 and 2016, heat caused an annual average of approximately £2 million in Schedule 8 compensation payments between Network Rail and TOCs. For lightning this was approximately £4 million and for wind £14 million (Network Rail, 2017a). These figures are for the whole of Network Rail's GB network (England, Wales and Scotland). The wider costs to the economy and society of major incidents are considerably higher than the cost to the infrastructure managers and TOCs, as exemplified by the July 2015 heat wave outlined above (estimated cost £16 million). Network Rail estimate that although the impact of weather on their business is £50-200 million (Network Rail, 2021), they estimate that this rises to £100-£300 million when considering social and economic impacts (a three to four fold rise). These figures indicate medium magnitude with high confidence.

#### 4.13.1.1.2 Roads (current risk)

High summer temperatures can increase thermal loading on bridges and pavements causing

expansion, bleeding and rutting, as demonstrated during the 2003 and 2006 heatwave events (Willway *et al.*, 2008). Wildfires can lead to road closures if the fire burns next to the road or crosses it, or if large volumes of smoke obscure vision. The Swinley Forest Fire in 2011 led to closure of the A3095 for a week which cost around £229,292 (Aylen *et al.*, 2015). Cold weather (including snow and ice) caused 16% of all weather-related delays to the strategic road network in England between 2006 and 2014 (ASC, 2014). Wind impacts road operations, with high sided vehicles becoming unstable in gusts of wind over 45mph (particularly on exposed bridges). High winds can also damage roadside furniture, such as traffic signs, and blow nearby vegetation onto the road. In a notable example, the opening of the Queensferry Crossing across the Forth in 2017 has allowed key transport and supply routes to remain open between Edinburgh, Glasgow and the Central Belt and the north of Scotland, due to increased wind shielding compared to the Forth Road Bridge.

The CCC (2019) observe that the strategic road network is younger than the rail network with most of the network built since the 1950s utilising modern materials and design. They state that Highways England are meeting performance targets, with 95% of the network in good condition. The local road network is considered to be particularly vulnerable to severe weather, as it makes up 98% of the country's road network, ranging from major 'A' roads to minor country lanes. They also cover a far wider range of geographic locations, and hence more varied microclimates (CCC, 2019).

In Scotland, a combination of topography and climate can increase risk. This includes steep slopes, higher altitude and exposure, loss of original tree cover, a more extreme climate and greater exposure to winter storms (Scottish Government, 2019b). Remote areas in the Scottish Highlands and islands are often served by single routes which can lead to isolation or detours during disruption.

The DfT Resilience Review (2014) stated that roads in better condition should be better able to withstand severe weather impacts, and that higher temperatures, flooding and geotechnical movement can speed up deterioration and lessen their resilience. The DfT's Road Condition report (2019) determined that following a period of gradual improvement, condition of classified local authority managed roads has remained stable in recent years. During the same period, unclassified roads had not seen the same level of improvement. Highways England managed motorway condition has gradually improved since 2007/8 (managed 'A' roads have fluctuated).

There is a general lack of quantified data on the impact of high and low temperatures, wind and lightning on road infrastructure, hence the score of 'low' for confidence.

#### 4.13.1.1.1.3 Air Travel (current risk)

Higher temperatures can cause problems with runway conditions and the flashpoint of aviation fuel. These factors, combined with changes in air density, would result in greater fuel usage and potentially longer runways for take-off (Heathrow Airport, 2016). Overheating of standing aircraft occurs at temperatures above 25-30°C and requires the use of aircraft Auxiliary Power Units (APU) or preconditioned air (PCA) to cool aircraft (Stansted Airport Ltd, 2016). Snow and ice can cause severe disruption to operations, as demonstrated by the heavy snow of December 2010 (Begg Report, 2011). Finally, Time Based Separations (TBS), such as those introduced in 2015 at Heathrow, can be

used to reduce delays and cancellations due to strong headwinds. This can add four plane movements per hour on strong wind days, leading to a 50% reduction in annual delays attributable to strong winds (Heathrow Airport, 2016).

#### 4.13.1.1.1.4 Water (current risk)

High wind speeds can lead to the suspension of port operations. For example, sustained wind speeds of 22 m/s or greater will result in the suspension of vessel operations at the port with any stoppages greater than four hours in duration being considered 'major stoppages' (Milford Haven Port Authority, 2015). It was particularly noted that 2014 had been a difficult year in respect of crane stoppages due to high winds. The Port of Dover (2015), reported a number of wind-related thresholds for different operations. For instance, the port is closed during sustained wind speeds above 55 knots from a South South Westerly and West South Westerly direction. A wind speed of 37 knots and above was given as a threshold for overtopping at Admiralty Pier. Lightning strikes were reported to cause temporary dips in power, causing failure of quay crane equipment (Felixstowe Dock and Railway Company, 2016).

**Table 4.49** UK-wide magnitude scores for current risks to transport from high and low temperatures, high winds, lightning

Risks to rail from high and low temperatures, high winds, lightning	Medium (High confidence)
Risks to roads from high and low temperatures, high winds, lightning	Medium (Low confidence)
Risks to air travel from high and low temperatures, high winds, lightning	Low (Medium Confidence)
Risks to water from high and low temperatures, high winds, lightning	Low (Low confidence)
<b>Overall magnitude scores for current risks</b>	<b>Medium (High confidence)</b>

#### 4.13.1.2. Future risk (I12)

##### 4.13.1.2.1. UK-wide

##### 4.13.1.2.1.1 Rail (future risk)

Evidence collected during CCRA2 indicated an eight-fold increase in the annual cost of buckling by the 2080s under a high emissions scenario using the UKCIP02 projections (Dobney *et al.*, 2009). Temporary speed restrictions were expected to quadruple from 0.5 to 2 days per summer season. In a scenario of 4°C global warming by 2100<sup>20</sup>, more frequent extreme temperatures are projected to reduce the number of days when track maintenance can be undertaken across the UK, with the greatest (threefold) increase in Scotland by the 2040s (Palin *et al.*, 2013). The exposure of staff working outdoors to heat stress is also projected to increase, most significantly in the south and east

<sup>20</sup> UKCP09 HadRM3 regional climate model 11-member perturbed parameter ensemble driven by the SRES A1B scenario.



of England where events could be 2–9 times more frequent by the 2040s (Palin *et al.*, 2013). However, there are projected to be opportunities arising from fewer snow and ice days to reduce winter maintenance costs (Dora, 2015).

Arnell *et al.* (2021) present a consistent set of policy-relevant indicators of changing climate hazards for the UK. For the rail sector temperature thresholds of 26°C and 30°C were identified in the literature as relating to rail buckling risk. The study also used Network Rail's adverse weather warnings thresholds which are set for sustained wind speed above 40mph, maximum temperatures above 25°C, minimum temperatures below 3°C, daily rainfall > 40 mm, snow depth > 50 mm or a diurnal temperature range of > 16°C. Projections for two of these indicators using scenarios of 2°C and 4°C global warming at 2100<sup>21</sup> is presented in Figure 4.12. The greatest increase in the transport indicators is seen in England and Wales. Scotland and Northern Ireland see shallower increases in heat-related transport indicators (although the indicators do not account for differences in the resilience of the networks in the UK and potentially lower thresholds / critical rail temperatures) and an initial decrease in adverse weather warning days as a result of reduced cold weather impacts (it must be noted this indicator includes hazards outside of the scope of this risk).

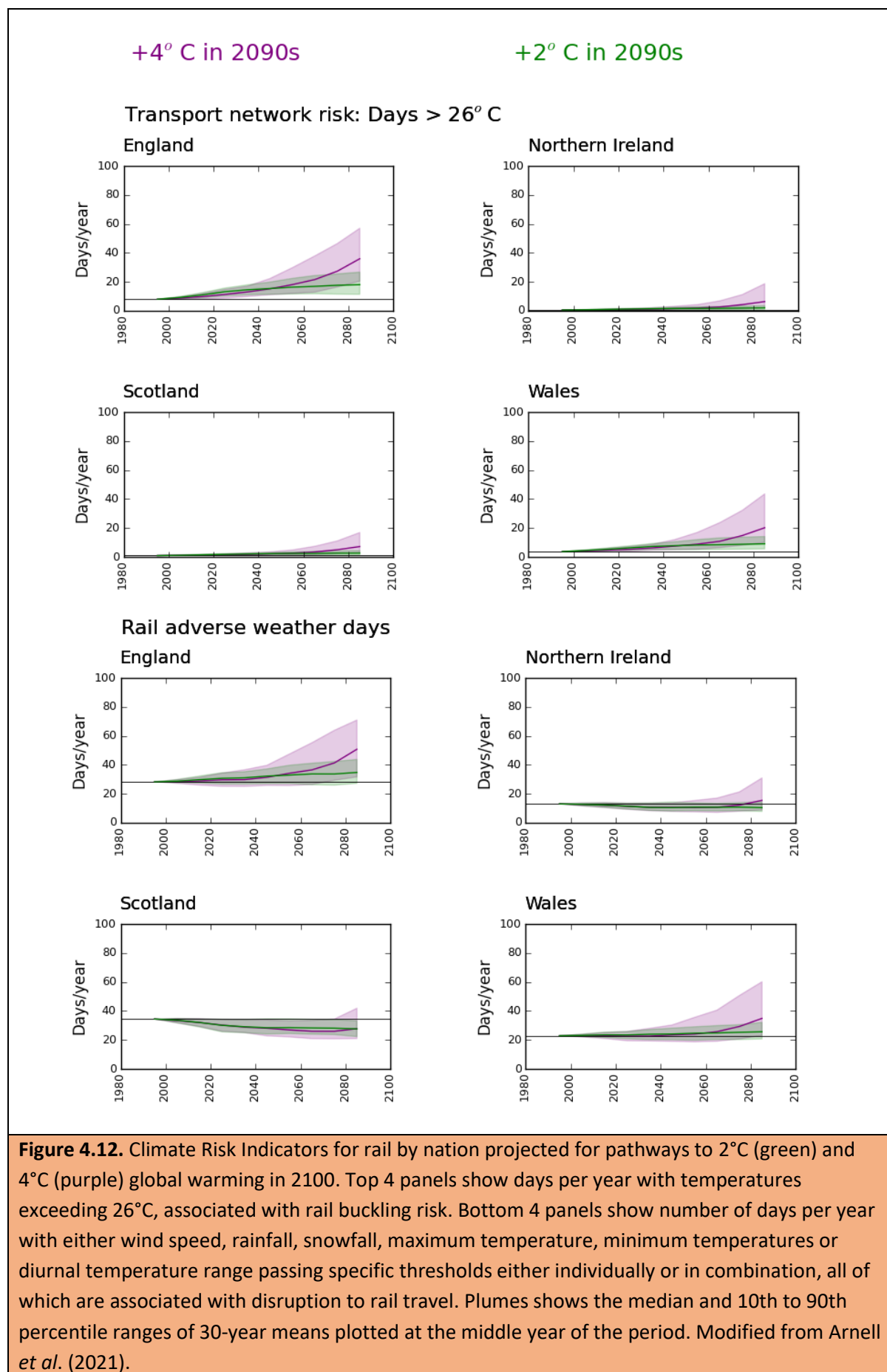
In a scenario of 4°C global warming by 2100<sup>22</sup>, the heatwave season is expected to expand from July–August to May–September by the 2040s, and by the 2080s over half the UK is projected to experience heatwave conditions at some point every year (Sanderson and Ford, 2016a). The advent of digital signalling systems such as the European Railway Management System (ERTMS), in the long-term (2050s), may remove a significant quantity of trackside signalling equipment (Ferranti *et al.*, 2018), potentially reducing heat-related risk to railway operations. The extent of impacts will also be mediated by future freight and passenger numbers and the availability of alternative modes of transport (cross-modal substitution is important across all components of the transport system). In the 2050s under the UKCP09 high emissions scenario, which warms faster than the CCRA3 higher scenario, all deep London Underground lines are projected to experience near complete passenger discomfort during the summer (Jenkins *et al.*, 2014).

Longer growing seasons were judged to increase vegetation growth rates, increasing the number of tree-related faults and disruption. However, large uncertainties surround the impact of climate change on vegetation making the possible outcomes for growth rates, species, and leaf fall difficult to ascertain (Carey, 2015). No projections existed for future storm or lightning damage to rail services. CCRA2 noted the need for better understanding of projected changes in maximum wind speeds and the frequency of such events.

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<sup>21</sup> Subsets of the UKCP18 probabilistic projections for which the global mean temperature anomaly reaches 2°C or 4°C above 1850-1900 in 2100.

<sup>22</sup> SRES A1B scenario



#### 4.13.1.2.1.2 Road (future risk)

Highway's England's Climate Change Risk assessment (2016) uses a scenario compatible with the CCRA3 pathway to 4°C global warming by the end of the century<sup>23</sup> to identify vulnerabilities. Using these projections, and research from the Conference of European Directors of Roads (CEDR), Highways England highlighted climate change hazards with potential to impact their services and network users. Amongst the risks highlighted with high importance were increases in maximum temperature with associated extreme summer temperatures and increased wind speed for the worst gales, leading to wind speeds more frequently exceeding operational limits. They also identify a number of operational or other thresholds for action including incidence of ground frost, temperatures above which asphalt surfaces rut or stripping occurs and the length of the frost-free season (allowing reduction in winter maintenance standby requirements). Although snow and cold temperature events may decrease, any associated reduction in preparedness or increased complacency may reduce the extent of any benefits. Weather conducive to wildfire is projected to occur more frequently in all UK countries (Arnell et al., 2021), so if this results in more frequent or severe fires near roads then disruption from reduced visibility due to smoke or direct threat of fire could occur more often. There is currently a lack of quantified projections for the impact of climate change on road infrastructure and operations.

#### 4.13.1.2.1.3 Air Travel (future risk)

It was stated in CCRA2 (Dawson *et al*, 2016) that the impacts of climate change on UK aviation were expected to be the least significant of all transport modes. Clear-air turbulence during the cruise phase of flights is projected to increase due to climate change, increasing journey length and fuel consumption. Williams and Joshi (2014) examined the effects on clear air turbulence at approximately 3°C global warming<sup>24</sup>, in December, January and February in the North Atlantic flight corridor between Europe and North America. They found a 10–40% increase in the median strength of turbulence at typical cruise altitudes, but with up to a 170% increase in the frequency of greater than moderate turbulence. Williams (2016) studied transatlantic crossings and projected that a strengthening of prevailing jet stream winds would cause eastbound flights to significantly shorten and westbound flights to significantly lengthen in all seasons, with round-trip journey times increasing.

Anticipated increases in temperature in UK airports and associated impacts are well within the range experienced by other international airports and can be managed operationally. Birmingham, Gatwick, Glasgow, Heathrow, Manchester Group (including East Midlands), and Stansted Airports all reported for ARP2. All used broad UKCP09 scenarios and a workshop approach to arrive at risk registers for key assets and functions. Gatwick used low, medium, and high scenarios at the 90% probability level at the 2020s and 2050s, with the medium scenario reaching 4°C global warming by the end of the century. However, no mention is made of heat, high winds or lightning in the identified risks or adaptation measures. Take-off weight restrictions for aircraft may be lowered, as warmer air reduces the lift force on the wings (Coffel and Horton, 2015).

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<sup>23</sup> SRES A1B scenario

<sup>24</sup> Projected with the GFDL CM2.1 climate model with CO<sub>2</sub> concentrations at double the pre-industrial level

## 4.13.1.2.1.4 Water (future risk)

It is recognised that projections of wind events are extremely uncertain, with no strong trend discernible (Met Office 2019b), acting as a barrier for their use to project future impacts (Milford Haven, 2016). The DfT's 2018 port connectivity study highlights the importance of interdependencies with other infrastructure, particularly the preparedness of the road and rail networks for climate change.

**Table 4.50** UK-wide magnitude scores for future risks to transport from high and low temperatures, high winds, lightning

Risks to rail from high and low temperatures, high winds, lightning	High (Medium confidence)
Risks to roads from high and low temperatures, high winds, lightning	Medium (Low confidence)
Risks to air travel from high and low temperatures, high winds, lightning	Low (Low confidence)
Risks to water from high and low temperatures, high winds, lightning	Low (Low confidence)
<b>Overall magnitude scores for future risks</b>	<b>High (Low confidence)</b>

## 4.13.1.3 Lock-in and thresholds (I12)

New linear infrastructure and ports planned for development have a long life-time and thus could be locked in to being at risk from future high temperatures, wind and lightning if climate change projections are not used to inform the location / route and design of these assets. Upgrades of existing infrastructure could lock in vulnerabilities associated with their location and/or choice of materials and equipment if climate projections are not considered as part of these plans.

Railway assets tend to demonstrate threshold temperatures, beyond which failures manifest. For example, Network Rail 'pre-stress' rail to a stress-free temperature (STF) of 27°C. Similarly, road surface coverings are also specified to certain range of temperature exposure. Any future increase in high wind speeds may also reduce the capacity of certain bridges and upland roads where high sided vehicles are at risk of toppling, increasing the case for alternatives.

## 4.13.1.4 Cross-cutting risks and inter-dependencies (I12)

WSP (2020) assessed impacts that are affected by a number of risks further up the chain of interactions. Travel and freight delays were found to have the largest number of upstream interactions, and the largest number of interactions across all the sectors analysed (infrastructure, built environment and natural environment). This indicates that risk emanating from other sectors

are more likely to cause travel delays. The most significant interaction contributing to travel delays was found to be the impact of heatwaves or very hot days leading to transport overheating and/or ICT services being disrupted, both in turn leading to transport delays and damaged infrastructure. This pathway was assessed as low risk in 2020 but becoming medium in 2080 under a pathway to approximately 4°C global warming in the late 21<sup>st</sup> Century, with large uncertainty<sup>25</sup>.

Other examples of interactions modelled in the interacting risks project include:

- Extreme summer temperatures and/or reduction in summer rainfall leading to wildfires, poor visibility and travel delay,
- Lightning, high winds, hail and ice, heavy snow, cold, and poor visibility, all leading to transport infrastructure or hub disruptions, leading to travel delay,
- Travel delays and disruption can have subsequent knock-on impacts to the built environment, for example through loss of productivity as people are unable to get to work, and impact on health and welfare if emergency personnel and services are unable to use transport.

#### 4.13.1.5 Implications of Net Zero (I12)

The Net Zero target is likely to have a large impact on the transport sector, both in terms of fuel substitution and modal shift. Increased electrification of rail will increase the risk of disruption caused by overhead line-sag and direct and indirect damage to lines during high wind events. However, alternative decarbonisation routes such as the introduction of hydrogen-fuelled trains would reduce exposure to these risks. A shift to more active modes of transport such as cycling may expose the public to a different set of weather-related risks when travelling (e.g. high winds).

#### 4.13.1.6 Inequalities (I12)

Access to transport infrastructure provides access to jobs and employment, key services and education opportunities. Those living in areas of transport poverty are likely more at risk from disruptions to individual transport modes, as they do not have the choice to use alternatives, exacerbating existing problems associated with poor accessibility. A particular problem is with islands, where any disruption to passenger and freight transport via air and sea can leave these communities and economies isolated.

#### 4.13.1.7 Magnitude scores (I12)

There are varying degrees of risk posed by the hazards presented in this section, as well as varying degrees of understanding and spatial disaggregation of the current and future risks between the different modes. Rail has the strongest evidence base for current risk. In England, Scotland and Wales, quantified costs to Network Rail run into the £10s of millions annually for the hazards under consideration (full social and economic costs are estimated in the high £10s of million). Current

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<sup>25</sup> UKCP18 probabilistic projections with RCP8.5 emissions, with the 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentiles reaching global warming of 3.0°C, 4.2°C and 5.8°C respectively in 2070-2099.

magnitude is given as medium with high confidence (Table 4.51). Given the high financial costs of infrastructure failure (particularly heat-related infrastructure failure on the rail network), this increase translates into a revised magnitude score of high across the UK. Confidence on future magnitudes is low as the assessment of impact of risks is variable across the different transport modes.

**Table 4.51** Magnitude scores for risks to transport from high and low temperatures, high winds, lightning

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Medium	High	High	High	High
	(High confidence)	(low confidence)	(low confidence)	(low confidence)	(low confidence)
Northern Ireland	Medium	High	High	High	High
	(high confidence)	(low confidence)	(low confidence)	(low confidence)	(low confidence)
Scotland	Medium	High	High	High	High
	(high confidence)	(low confidence)	(low confidence)	(low confidence)	(low confidence)
Wales	Medium	High	High	High	High
	(high confidence)	(low confidence)	(low confidence)	(low confidence)	(low confidence)

#### 4.13.2 The extent to which current adaptation will manage the risk (I12)

##### 4.13.2.1 Effects of current adaptation policy and commitments on current and future risks (I12)

Each UK nation has cross-sector adaptation plans for transport. For example, the Future Wales: National Plan 2040 (Welsh Government, 2021a) and Llwybr Newydd: Wales Transport Strategy (Welsh Government, 2021c) provide an opportunity to build adaptive management approaches in Wales to road, rail, air and water-based transport planning and investment. Each has high-level commitments to develop the resilience of transport infrastructure to the effects of climate change. Similarly, the Wales National Infrastructure Commission has recognised the importance of this issue. In Scotland, the new National Transport Strategy for Scotland (2020) guides improved resilience for the road network. The Perceptions of Trunk Road Networks in Scotland survey continues to collect data on disruptions to journeys by road due to severe weather.

#### 4.13.2.2 Effects of non-governmental adaptation (I12)

##### 4.13.2.2.1 Rail

Network Rail produces regional Route Weather Resilience and Climate Change Adaptation Plans for each of their operational routes in England, Wales and Scotland. These identify priority resilience measures using the UKCP09 medium emissions scenario at the 90<sup>th</sup> percentile (equivalent to a 4.2°C global temperature increase by 2100). The high emission scenario is used for assets with longer operational lifetimes. These are being updated for the next Control Period (2019–2024). The CCC gave Network Rail's adaptation plans and progress to date a high score in their progress report (2019). They state that the plans set out actions, timeframes, accountabilities, and responsibilities for implementing resilience measures, and that they act as a good starting point for a framework to embed adaptation and resilience into policies, standards, decisions and investment.

The CCC (2019) report that Network Rail is undertaking further adaptation actions beyond those set out in NAP2. These include the requirement to consider climate change risk in new infrastructure projects and embedding adaptation requirements within business as usual activities through guidance, data and tools (updated to take into consideration UKCP18 projections). It is also reported that asset teams are conducting climate change risk assessments and developing strategies and action plans from an asset management perspective which will lead to updated design, operation and maintenance standards. Results of these undertakings will feed into ARP3 reports. Network Rail are also conducting research projects to assess the vulnerability of assets and prioritise action (this includes improving understanding of the real cost of weather resilience and climate change adaptation). Other plans include the development of resilience metrics and the development of improved understanding of the interdependencies within Network Rail and wider UK infrastructure systems.

Train Operating Companies are encouraged in Rail Delivery Group's Key Train Requirements document to improve the resilience of their rolling stock. This guidance informs train design franchise specifications, and specifically references lifetime resilience of rolling stock to a range of climate conditions (although it doesn't utilise scenarios).

The (London) Mayor's Transport Strategy (2018) includes an aim to improve the evidence base for cost-effective long-term climate adaptation in Greater London. Identified risks will be addressed through construction and asset renewal, ensuring major projects are climate-proofed for their intended lifetime, and identifying high-priority locations for resilience interventions.

The CCC (2019) conclude that the actions in NAP2 are likely to be reducing vulnerability in some areas in England. However, without better indicators available it is hard to assess their impact. It is also mentioned that actions are currently focussed on flood risk, slope stability and bridges.

In Northern Ireland, Translink (DAERA, 2019) have committed to carry out a detailed tree survey which will examine the risk of tree related incidents due to high wind events. Translink have also committed to carry out a project to update the Stress-Free Temperatures records for rail and to identify locations that could be at risk during extreme heat.

There are a number of policies in the Scottish Climate Change Adaptation Programme (Scottish Government, 2019b) related to adaptation of rail infrastructure. The new National Transport Strategy for Scotland (Scottish Government, 2020) includes a Policy to 'Ensure the transport system adapts to the projected climate change impacts'. Network Rail has produced a Route Weather Resilience and Climate Change Adaptation Plan for Scotland which incorporates a number of programmes and initiatives designed to increase resilience of the railway in Scotland to effects of weather and climate change including sub-programmes focussed on infrastructure resilience against extreme temperatures and high winds. The plan includes an assessment of current and future vulnerability of the rail network to climate impacts.

Quarterly monitoring of Network Rail and ScotRail services includes disruption due to the impacts of severe weather. The Office of Rail Regulation continues to publish a Quarterly Monitor on National Rail performance and Transport Scotland manages the performance of ScotRail across all areas including disruption due to the impacts of severe weather. Scottish Ministers also require Network Rail to work with the rail industry to develop and apply suitable KPIs for monitoring the impact and mitigation of climate change upon network disruption and the means of measuring the benefits of adaptation interventions.

#### 4.13.2.2.2 Roads

The UK Roads Liaison Group's 2016 'Code of Practice: Well Managed Highway Infrastructure' (UKRLG, 2016) asks local authorities to utilise the UKCP18 projections for future risk and vulnerability assessments to ensure that infrastructure is located, planned, designed and maintained to be resilient to climate change.

Highways England (2017) high-level strategy document on Environment contains the ambition to ensure climate resilience is embedded in business-as-usual activities, taking into account evidence from UKCP18. The report highlights actions to mitigate increases in mean temperature (such as reviewing design standards for pavement construction) and increases in wind speeds (including monitoring the potential impact of wind on structures such as gantries to ensure design standards are appropriate). The CCC (2019) rated the strategic road network's adaptation plans as high and risk score as medium. Highways England's assessments use a high emission scenario (over 4°C global warming by the end of the century) and identify network vulnerabilities, with this information being used to update operational procedures and adaptation plans. Highways England look across all climate hazards including precipitation changes, increases in mean temperature and increases in wind speeds.

The CCC (2019) make reference to the Government's resilience Incentive Fund, which local highway authorities in England outside of London can apply for if they can show they have processes to manage extreme weather. Local road's adaptation plan and risk were both rated as medium (CCC, 2019). It is not clear from the available evidence whether there has been a systematic evaluation of climate change risks to either the local road network or to local highway bridges. Better indicators are needed to assess progress in managing the impact of climate risks on local roads.



#### 4.13.2.2.3 Air Travel

Apart from Gatwick and Heathrow airports, which have economic licence conditions mandating the preparation of resilience plans and are therefore incorporated into their business plans, the CCC (2019b) notes that work on reducing vulnerability at most airports has mostly been reactive and the Government does not have a way of mandating resilience actions. CCC (2019b) highlights that the draft Aviation 2050 Strategy consultation proposes that Government work with the aviation industry to improve resilience to weather and refers to climate change in terms of reducing emissions but not adaptation to scenarios of 2°C or 4°C global warming.

Glasgow Airport (2016) identifies several barriers to implementing possible climate change adaptation measures. These include environmental fiscal taxes, difficulty in justifying the business case in terms of internal rates of return, regulatory constraints (evolution of new/tighter financial controls potentially restricting airports' ability to invest in measures that are not integral to meeting compliance requirements). In contrast, Heathrow Airport (2016) has begun the planning process for the next regulatory period (2019–2023). This includes a climate change adaptation risk register and incorporating climate change adaptation into business planning process.

CCC (2019b) identifies that NAP2 includes only one action for airports. This is focused on improving the understanding of risk rather than reporting on reducing vulnerability or exposure. The ARP3 reports will include climate risk assessments and steps to increasing resilience, but these are not mandatory for all airports.

#### 4.13.2.2.4 Water

Ports are not subject to economic regulation. As a result, there is a general lack of data regarding the overall resilience of ports compared to most other regulated sectors. This means it is difficult to tell whether lessons from the winter of 2013/14 have now been learned and whether the disruption witnessed is likely or not to be repeated. Equipment in ports typically has a 20 to 100-year design life. Several ports are collaborating with other local partners to co-fund adaptation options to the benefit of ports and surrounding areas. Felixstowe port is installing equipment capable of monitoring lightning strikes which may impact on power supply continuity. This will allow the port to react, thus limiting down time / damage to equipment (Felixstowe Dock and Railway Company, 2016). Tarmac is also being replaced by more heat resilient surfaces. Most hard surfaces are covered by material that is more heat resistant than tarmac. In 2019, the CCC found that there presently isn't data to assess whether steps are being taken by ports in Scotland to manage the increase in severe weather impacts and disruption to services in future. Information that would enable an evidence-based assessment of the vulnerability might include time-series data on the number of disruptions caused by extreme weather events and the level of investment being made in improving standards of resilience.

#### 4.13.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I12)

The risk is only partially being managed. Although there are examples of good practice within individual transport modes such as road and rail and emerging activities taking place, the approach

to managing climate risks across transport infrastructure is not comprehensive.

#### 4.13.2.3. Adaptation scores (I12)

<b>Table 4.52</b> Adaptation scores for risks to transport from high and low temperatures, high winds, lightning			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

#### 4.13.3 Benefits of further adaptation action in the next five years (I12)

##### 4.13.3.1. Additional planned adaptation that would address the adaptation shortfall (I2)?

In a study on the influence of uncertain asset stock data on the assessment of climate risks for railways in Great Britain, Dikanski *et al.* (2018) found that avoidable uncertainty in basic asset data (in this case related to bridge scour), can outweigh uncertainty in climate projections by an order of magnitude. They identify better asset information collection by infrastructure managers as a quick win for effect climate adaptation.

Heat-related rail buckling (and other heat-related asset failures) is a clear risk to future rail operations. CCC (2019) report that planned levels of future activity are appropriate and should continue to be implemented to ensure risk is managed. Moreover, the CCC report that actions being taken to reduce risk by the rail industry are likely reducing vulnerability in some areas, but evidence is currently lacking. This may be due to the current indicators of resilience (delay data), which may not directly indicate how the physical vulnerability of assets is changing. The Tomorrow's Railway and Climate Change Adaptation (TRaCCA) project (RSSB, 2016b) made a number of recommendations to Government including enhanced weather incident reporting and asset condition monitoring and revised standards (for instance, increasing the stress-free temperature of steel rail in line with future climate projections). The CCC (2019) observe that although Network Rail's route plans contain relevant actions and consider a scenario of 4°C global warming by 2100, the strategy provides guidance to prepare for future action rather than specific measurable goals to reduce risk.

For local roads, the CCC (2019) conclude that it is not clear whether there has been a systematic evaluation of climate change risks. Similarly, to rail, it is recommended that better indicators of climate resilience for roads are developed.

For ports and airports, it is clear from the CCC (2019) report that lack of engagement with the ARP process may be a barrier to adaptation. Although 16 ports and airports submitted to ARP2, another six declined to participate. The CCC argue that without making the Adaptation Reporting Power mandatory, it is hard to be assured that risk is being managed in the sector as a whole. Similarly to

road and rail, improved data on disruption to ports and airports would assist in assessing current and potential future risk.

#### 4.13.3.2 Indicative costs and benefits of additional adaptation (I12)

In general, there are a set of no regret options in the form of improved weather and climate services, including early warning systems, for extreme risks for transport, which have been found to have high benefit to cost ratios across modes from the avoided damage and thus value of information (Clements *et al.*, 2013). There are further opportunities for these options, and general management of weather related risks through digital platforms, remote sensing, etc., and their use in real time network management (EEA, 2014), which can be considered no-regret because of the reduced costs of disruption and thus economic benefits in terms of travel time (ToPDAd, 2015).

The potential risks of high temperatures on the rail networks, and the potential economic costs of rail buckling risks under climate change have been previously estimated in the UK (e.g. Dobney *et al.*, 2009, Alvater *et al.*, 2012). The reactive adaptation response to these has been speed restrictions, although these have important travel time costs. There has been some analysis of the cost-effectiveness of options to address these risks, though these are mostly focused on improved risk assessment and monitoring (RSSB, 2016). There are potential rising risks from wind and vegetation growth, which are likely to mean increased vegetation management costs (which can be considered an impact or an adaptation).

There has also been analysis of the potential economic costs of heat on highways (including rutting and user delay costs, as well as additional capital maintenance costs) and the costs and benefits of addressing heat risks to highways (Atkins, 2013a). This considers technical surfacing options and found a modest positive net present value and cost-benefit ratio of slightly greater than 1. Alvater *et al.* (2012) also investigated the additional costs of using better asphalt for roads in the UK, and found the costs generally outweighed the benefits. There is also a large international literature in this area (from warmer countries), which highlight improved maintenance practices, risk assessments, early warning, and enhanced design standards for roads (e.g. EEA, 2014, Ecofys, 2016). There are other approaches, e.g. with greater redundancy in road networks, but these involve significant extra costs. There is also emerging focus on focusing adaptation investments on the vulnerability hot spots on networks, i.e. to identify the points on the system where greater resilience would be most cost-effective (as part of network level analysis rather than for individual assets). While this has mostly focused on flooding (Oh *et al.*, 2020), the same approaches could apply to other risks.

For existing infrastructure, improved monitoring and information, and also improvement of maintenance practices and operations, are considered low-regret adaptation options. For new infrastructure, there are opportunities for mainstreaming climate change adaptation into planning and design, to avoid retrofitting later. The balance of costs and benefits for such approaches depends on the costs, the timing and level of discounted future benefits, as well as the costs of retrofit later. This means some, but not all measures are likely to have positive NPVs and these may be site specific. There is the potential for decision making under uncertainty approaches for new transport infrastructure (e.g. considering flexibility, robustness, adaptive management) but these have important time and resource implications. The main risks of lock-in, and thus main role for such

approaches, are for new roads, rail, etc. (rather than refurbishment or upgrades) due to siting decisions.

#### 4.13.3.3 Overall urgency scores (I12)

The understanding of current and future risk from climate impacts is varied across different transport modes and climate hazards. While there are examples of good practice within individual transport modes such as road and rail and emerging activities taking place, the approach to managing climate risks across transport infrastructure is not comprehensive. Action is also needed to avoid locking in new climate vulnerabilities in the shift to electrified and other lower carbon forms of transport. It is acknowledged that the split between more action and further research will vary between modes, climate hazard and nation.

**Table 4.53** Urgency scores for risks to transport from high and low temperatures, high winds, lightning

Country	England	Northern Ireland	Scotland	Wales
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Medium	Medium	Medium

#### 4.13.4 Looking ahead (I12)

There is a need for the transport system to be assessed on a whole-system basis, both within modes and between modes. By treating mobility as a whole system (and considering the full range of climate-related risks to transport identified, such as those in risks I1, I2, I3, I4, I5 and I7), targeted, cost-effective adaptation measures can be taken which will ensure the movement of people and goods. This will require a greater level of understanding on how individual components within the individual transport networks respond to weather in the present day and how climate change may affect failure rates of these assets. Solving the problem of avoidable uncertainty in basic asset data (Dikanski *et al.*, 2018) is essential to achieving this. Asset condition monitoring and a greater use of sensors and localised weather stations will help build this understanding, which can be fed through into climate impact studies. The progress report on adaptation (CCC, 2019) states that there is a need for better understanding of projected changes in maximum wind speeds and the frequency of such events.

The resilience of future electrified transport systems needs to be formally assessed to identify and map new interdependencies with the electricity generation, transmission and distribution network, the digital/CT sector, as well as within the wider supply chain. Similarly, risks to transport from intense periods of heavy rainfall, and implications for visibility were not considered within this CCRA and could warrant further consideration particularly for aviation, shipping and road transport. Further information on the activities of the Airport Operators Association and the British Ports Association on adaptation would be useful to determine any current adaptation shortfall.

There is currently a lack of evidence on the potential impact of climate change on rivers and

waterways. This has links with Net Zero considerations, such as plans to encourage use of water-based travel such as London's Blue Ribbon Network.

#### 4.14. Risks to digital from high and low temperatures, high winds and lightning (I13)

The current risks to digital are assessed to currently be of medium magnitude and will increase to 'high' under the most extreme scenario considered in this assessment. However, the evidence to support this is of low quality. While there is a general understanding of the interactions between ICT infrastructure and weather, quantitative projections assessing how climate change will affect the frequency and magnitude of these interruptions are lacking. This makes it difficult to assess the exact level of risk to the sector and is compounded by little information on the location or specification of assets being in the public domain for interests of security and commercial sensitivity. ICT is critical to the operation of wider infrastructure networks as well as underpinning business activities, access to key services and wider communication. Outages can therefore have significant effects on the locality and more broadly via interdependent infrastructure. While there exist different levels of access to both the internet and mobile phone coverage across the UK, the evidence is insufficient to establish with confidence any difference in risk between the devolved administrations. Reliance on ICT for the operation and control of components in the infrastructure system in isolation and as a whole is increasing, meaning the potential risk to infrastructure from ICT failure will increase in the future. Overall, further attention to the climate resilience of this sector and quantitative information on current and future risks under climate change is needed to better assess its vulnerability and exposure to climate change.

##### 4.14.1 Current and future level of risk (I13)

Note: It has not been possible to split the evidence by UK country for this risk.

###### 4.14.1.1. Current risk (I13)

###### 4.14.1.1.1. UK-wide

Climate-related risks have the potential to disrupt the availability and reliability of the ICT sector and consequently push up operational costs for users (ITU, 2014). Increasingly, infrastructure such as water, power and transport are controlled over the telecommunications networks. Failure of telecommunications can lead to reduced capacity in a wide range of other essential services. Cross-sector resilience issues, and the reliance of telecommunications on the electricity network, was considered by the UKRN (2016).

The mass production, standardisation and the relative ease of transportation of many ICT infrastructure components, means disruptions are typically localised and short-lived. Components are made for a global market and so designed for weather much more extreme than that experienced in the UK.

Increasingly the user instrument is a smartphone relying upon radio access to a base station. Mobile base stations are typically sited closer to the customer than fixed line exchanges. They are also less likely to have power back-up. This increases vulnerability to local threats such as mains electricity interruption and weather impacts such as flooding (Ofcom, 2015).

ICT networks also typically exhibit considerable resilience due to the diversity of suppliers and associated network topology and redundancy. Failure of part of a network is likely to have little, or no, effect on communications outside the area directly serviced by the failed component. However, this could still be significant locally were an event to require emergency services response, hampering communication as well as members of the public who may be at risk. As businesses and members of the public increasingly rely upon ICT systems for work, accessing services, leisure and social support, even local outages can cause significant disruption to those affected.

Data from Ofcom identifying outage incidents to networks and services between 2016 and 2017 showed that 1% (5 out of 648) of incidents were caused by severe weather (flood, storms or snow). In particular, the edges of networks where diversity is at its least are at risk of failure – typically near sparsely populated areas, or remote locations, such as islands, where loss of ICT for communication or control of other systems can cause significant problems. The implications of outages caused by weather for loss of emergency services communications, business revenue and social disruption indicates medium magnitude.

The accessibility to both internet and mobile network coverage vary between Wales, England, Northern Ireland and Scotland with 3, 2, 5 and 4% of premises respectively without access to download speeds of 10Mbit/Sec and 5, 1, 1 and 13% respectively without mobile call service. If this is taken as an indicator of the potential numbers of customers currently on the edges of networks and so more liable for disruption; the magnitude is higher for Scotland in particular, as well as Wales and Northern Ireland, compared to England. Without a better understanding of the exposure of ICT infrastructure across the UK it is difficult to differentiate the magnitude between the devolved administrations.

Over the last decade, the direct effects of climate change on radio propagation have become clearer. A large proportion of communications is over radio links, to mobile or nomadic devices, on fixed links as part of backbone networks or last-half-mile connections to a fibre network, or via satellites. All radio systems experience periods of unavailability due to variable attenuation associated with weather parameters. Changes in several weather parameters have already been observed, potentially attributable to climate change, affecting different frequency ranges. For example, the availability of fixed links operating at frequencies above 5 GHz is limited by the incidence of moderate or heavier rain. Over the last 25 years in the UK, trends have been observed in the incidence and characteristics of rain that directly affect the performance of these radio systems. The incidence of moderate or heavier rain is increasing and there is evidence that the spatial extent of these rain events may be decreasing (Paulson, 2016). These changes partially cancel but may lead to increased rates of outage on these links (Ofcom, 2012). This may require a future reduction in link densities or the retrofitting of systems for interference cancellation.

#### 4.14.1.2. Future risk (I13)

##### 4.14.1.2.1. UK-wide

International design standards for equipment embed a resilience to a changing climate in the sector. For example, most cables are designed to operate in global extremes of temperature, and so current and projected changes to UK temperature extremes are unlikely to have detrimental effects. The communications industry also has to deal with problems caused by severe weather conditions on a regular basis. The most serious issues for telecoms providers during periods of severe cold, snow or flooding, is the denial of access to affected sites, or loss of power (EC-RRG, 2018). These risks decline as more robust, underground, fibre optic cables parallel or replace aerial cables and wireless links. Fibre and cables are vulnerable to flooding damage where they use bridges to cross rivers.

The national optical fibre networks carry the bulk of telecommunications data. Closer to the user, fixed line calls and broadband data services rely on a root and branch network comprising trunk cables and exchanges, telephone lines strung between telegraph poles, and street cabinets that serve individual areas. An increase in the frequency or intensity of storms would increase the risk of wind, ice and snow damage to overhead cables and damage from wind-blown debris. These fixed line services are being replaced by wireless services (4G and 5G) from the nearest fibre node, and direct connection to fibre networks.

More intense or longer droughts and heatwaves can affect a range of ICT infrastructure because ground shrinkage can lead to failure of electrical, gas and water pipes, thereby damaging co-sited ICT infrastructure (CCC, 2019). Similar climatic conditions, further aggravated in cities by the urban heat island effect, place additional demands for cooling on energy networks increasing the risk of ‘brown out’ due to a reduction or restriction in power (Chapman *et al.*, 2013). High summer temperatures, as well as rapid fluctuations in temperature and humidity, pose challenges particularly to data centres, which need to be kept cool to operate (CCC, 2019). Data centres are also vulnerable to floods, high winds, wildfire and droughts as well as loss of supporting power supply (Uptime Institute, 2020). Data centres are increasingly critical to the function of organisations that operate on the cloud. The knock-on impacts of data centre outage may be national and international in nature.

There is limited information on the location of UK ICT infrastructure, making it difficult to make a rigorous and quantitative assessment of risks to ICT networks and services. The ownership of a large proportion of ICT infrastructure, particularly data centres, base stations and network connections are spread across the private sector. Information on location and connectivity is not publicly available, for commercial or security reasons, and so it is difficult to assess vulnerability to extreme events.

A warming climate will lead to changing experience of mixed phase hydrometeors (sleet) on many links that could lead to dramatic changes in availability rates, either for the better or worse. The increasing altitude of the boundary between liquid and solid hydrometeors leads to greater rain attenuation on links to satellites (Paulson and Al-Mreri, 2011). At lower frequencies, changes in interference due to ducting has been postulated. Higher temperatures are associated with stronger atmospheric ducts near the sea surface caused by water vapour from evaporation, but less ducting

at higher altitudes. Ducts over the North Sea and English Channel lead to higher levels of unwanted signals coming from Continental Europe that interfere with signals originating from the UK. Projected increases in sea surface temperatures are likely to lead to stronger ducting effects and communications disruption (Mufti and Siddle, 2013), including increased interference with VHF/UHF systems.

#### 4.14.1.3 Lock-in and thresholds (I13)

The short life span of some ICT/digital communications equipment should act to limit lock-in. However, towers and buildings such as data centres, have multi-decadal life spans and their location determines their exposure to extreme events such as flooding or wildfire.

Networks are sized to meet peak capacity levels; if these are exceeded, outages can occur. There are also thresholds related to operating temperatures of ICT equipment, additional cooling may be required to continue to maintain equipment at operational temperatures during heat waves. The choice of cooling equipment is important to avoid lock-in to high energy and/or carbon intensive provision or cooling systems which are unsuited to future climate. Furthermore, some cooling equipment may create further vulnerabilities to climate change such as the effects of water restrictions, or high humidity levels on evaporative cooling systems (Uptime Institute, 2020).

#### 4.14.1.4 Cross-cutting risks and inter-dependencies (I13)

In terms of interacting risks, access to sites during disruption is important. Maintenance and repairs rely on the transport sector and WSP (2020) highlighted the implications of a heatwave event causing disruption on IT networks leading to transport delays (which could also be associated with overheating risk to passengers). This pathway was assessed in the project as having a low risk in 2020, increasing to medium in 2080 under in a scenario of approximately 4°C global warming in the late 21<sup>st</sup> Century, with large uncertainty<sup>26</sup>. Data centres and wider network infrastructure are also dependent on electricity supply; any disruption to supply through flood, wildfire and heat waves may cause loss of service.

Other infrastructures may currently be less vulnerable to ICT disruption, but increased pervasiveness of ICT, particularly as a result of the increased uptake of ‘smart’ systems, is altering the interdependent risk profile of many infrastructure sectors and little is understood about the longer term implications of this for climate change risks. WSP (2020) highlighted disruption to IT and communication services as the second highest number of knock-on impacts in the infrastructure sector (second to power supply disruption). IT and communications disruption was also found to be significant based on impacts and likelihood meaning it is one of the most important contributors of risk through the different interacting pathways. Fundamentally, ICT is a major driver for productivity as people are unable to work, travel delays, water supply and sewage treatments.

There are potentially high levels of interdependency and vulnerability to ICT disruption in many

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<sup>26</sup> UKCP18 probabilistic projections with RCP8.5 emissions, with 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentiles reaching global warming of 3.0°C, 4.2°C and 5.8°C respectively in 2070-2099.



areas of industry, which is considered in Chapter 6 (Surminski, 2021). This is particularly the case in industries operating processing plants and equipment (such as oil refineries, gas processing plants, chemical and petrochemical plants, food processing facilities, etc.) which have high reliance on ICT for plant operations, monitoring, remote diagnosis of faults, etc. These industries are vital to the economic well-being of the UK and their disruption can have significant national and local economic and social implications.

#### 4.14.1.5 Implications of Net Zero (I13)

Building and maintaining ICT infrastructure requires energy. Much of a data centre's energy consumption is used for cooling and there is a risk to Net Zero of lock-in of mechanical cooling equipment that uses high GWP refrigerants, resulting in Greenhouse Gas emissions. Although equipment is becoming more energy efficient, the amount of equipment is growing quickly. ICT electricity use is predicted to double to 10–20% of global generation by 2030. This electricity will need to come from low-carbon sources or ICT growth could make Net Zero more difficult to achieve. ICT also has a large contribution to make in reaching Net Zero through the growth of smart grids, smart buildings, smart metering, logistics, real time navigation, e-commerce, e-learning, tele-presence, and environmental monitoring. These reduce the need to physically move goods and people and reduce the use of fossil fuels. Adverse effects on ICT due to climate change will have a significant detrimental effect on these sectors ability to deliver Net Zero.

#### 4.14.1.6 Inequalities (I13)

Inequalities are predominantly linked to geographic location and associated risks of wind damage, flooding and cascade risks. Sites near the edges of networks have the least redundancy and are often in remote areas, sometimes with rough terrain and limited access. These sites take longer to reach and repair after failures. Existing network access can be low in remote rural communities. There remain a significant number of premises unable to access download speeds of 10Mbit/s: 3, 2, 5 and 4% and without mobile (2G, 3G or 4G) coverage of 5, 1, 1 and 13% for Wales, England, Northern Ireland and Scotland (National Infrastructure Commission for Wales, 2019).

#### 4.14.1.6 Magnitude scores (I13)

In an analysis of interacting risks for CCRA3, WSP (2020) highlighted disruption to IT and communication services as having the second highest number of knock-on impacts in the infrastructure sector (second to power supply disruption). The impact of other hazards such as flooding has been observed to cause significant disruption, both through cascading failure from other systems such as power loss, leading to mobile base station outages in Lancaster following Storm Desmond in 2015 (reported in I1), as well as directly such as the flooding of a datacentre in Leeds in 2015 (reported in CCRA2: Dawson *et al.*, 2016). However, the evidence base on the specific impacts of high and low temperatures, high winds and lightning on ICT infrastructure is limited. The authors found no current evidence of significant disruption caused by these hazards on UK ICT infrastructure, hence a score of low but with low confidence owing to the limited evidence base in this area (Table 4.54).

**Table 4.54** Magnitude scores for risks to digital from high and low temperatures, high winds, lightning.

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Low	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Low	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Low	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Low	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

The need for datacentres to be kept cool to operate, as well as the potential impact of longer droughts or heatwaves causing ground shrinkage and failure of co-sited electrical, gas and water pipes with associated knock-on impacts to ICT, indicates a potential increased source of risk in all future scenarios in this assessment. The authors consider that the increased hazard profile combined with the increased pervasiveness of ICT and the observed magnitude of impacts of ICT failure caused by other hazards justifies a score of medium in all future scenarios in this assessment. The confidence in this assessment is low due to the lack of evidence base in this area. Quantitative projections assessing how climate change will affect the frequency and magnitude of interruptions to digital services are lacking (at least in the public domain). Without a better understanding of the exposure of ICT infrastructure across the UK it is difficult to differentiate the magnitude between the nations of the UK.

#### 4.14.2 The extent to which current adaptation will manage the risk (I13)

##### 4.14.2.1 Effects of current adaptation policy and commitments on current and future risks (I13)

Currently adaptation appears from the evidence to be reactive or unplanned due to the short life span of equipment. The most vulnerable assets requiring protection are masts, cables and buildings (including data centres in particular which are vulnerable to any disruption to cooling systems).

#### 4.14.2.1.1 England

The second National Adaptation Programme (Defra, 2018) states that the Department for Culture, Media and Sport are working with the telecoms industry via the industry-run Electronic Communications Resilience and Response Group, which leads on resilience in the sector. The actions mentioned in the NAP only relate to flooding however, and it remains unclear how far other hazards are being considered.

#### 4.14.2.1.2 Northern Ireland

The risks to digital from extreme heat, high winds and lightning are acknowledged in the Northern Ireland Climate Change Adaptation Programme 2019-2024 (DAERA, 2019), though there are no specific actions listed that relate to improving resilience of digital infrastructure specifically. The programme also states that digital infrastructure services in Northern Ireland operate independently from the Government with providers having their own responsibility to develop and monitor their own climate change resilience strategies. This includes business continuity measures in relation to climate change impacts, such as the provision of essential services which enables them and their customers to function.

#### 4.14.2.1.3 Scotland

The Scottish Government Climate Change Adaptation Programme 2019–2024 includes recognition of the climate risks to digital ICT infrastructure and its importance in delivering resilience (Scottish Government 2019b). ‘Keeping Scotland Running’ has been designed to support critical infrastructure owners and operators, emergency responders, resilience partnerships (RPs), industry groups and relevant government departments in working together to improve the resilience of critical infrastructure and essential services provision in Scotland. Digital infrastructure is considered an essential service. The ‘Keeping Scotland Running’ Guidance Suite seeks to support the delivery of Scotland’s Critical Infrastructure Resilience (CIR) Strategy and includes guides on Cyber Security and Critical Infrastructure, Resilience to Natural Hazards and Building Resilience to a Changing Climate (Adaptation)

#### 4.14.2.1.4 Wales

The Welsh Government climate change adaptation plan, Prosperity for All: A Climate Conscious Wales (Welsh Government, 2019b) and associated consultation (Welsh Government, 2019c) refers to resilient digital infrastructure as a key cross-cutting interdependency. The Welsh Government has committed to strengthen preparedness against multiple risks to interdependent infrastructure networks via pilot emergency response exercises, local resilience for an emergency response, and working with utility companies on electricity transmission network failure (Welsh Government, 2019b; 2019c). The National Infrastructure Commission for Wales should be considering this as part of their call for evidence and work on national approaches to digital infrastructure. There is no evidence on the level of engagement within the industry, or for SMART objectives to manage risk.

#### 4.14.2.2 Effects on non-government adaptation (I13)

There is no clear plan or process by the industry or Government with actions to manage long-term climate risks to the sector. CCC (2019) identify the lack of available data to assess vulnerability as a key barrier to adaptation, although some progress has been made on flooding (not covered in this risk but covered in I2 and I3). It also stated that although Ofcom provides guidance on maintaining services during flood events, guidance is not given on adaptation to climate change.

#### 4.14.2.3 Is the risk being managed? What are the barriers preventing adaptation to the risk? (I13)

While the risks to digital networks are recognised as an issue in all of the UK national adaptation programmes, there is a lack of evidence in the public realm of specific adaptation actions that will manage the specific risks of high and low temperatures, high winds, lightning down to low magnitude levels. It is acknowledged that the short generation times of particular components may by default manage risk in certain areas, but there is no evidence that non-government adaptation for longer-life infrastructure such as data centres will manage the risk. It is therefore considered the potential risk identified in Step 1 of this assessment is not currently being managed.

#### 4.14.2.4 Adaptation scores (I13)

<b>Table 4.55</b> Adaptation scores for risks to digital from high and low temperatures, high winds, lightning			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
No (Low confidence)	No (Low confidence)	No (Low confidence)	No (Low confidence)

#### 4.14.3 Benefits of further adaptation action in the next five years (I13)

##### 4.14.3.1. Additional planned adaptation that would address the adaptation shortfall (I13)

Further adaptation would include incorporating digital infrastructure into existing infrastructure climate adaptation plans recognising the criticality of ICT provision for wider infrastructure and society. Further information is also needed to identify and protect assets at risk of flooding and wildfires together with a better understanding of future impacts on radio communication VHF/UHF systems.

##### 4.14.3.2 Indicative costs and benefits of additional adaptation (I13)

While there is some information on adaptation options for the digital and ICT sector (Horrocks *et al.*, 2010), there does not appear to be a large literature on the costs and benefits of adaptation. There is a general low regret option to ensure better information on such risks, as well as to ensure climate risk assessment is included in design (and financial and economic appraisal, see also the

supplementary Green book Guidance on accounting for climate change, Defra, 2020a). It is noted that the sector typically has short design lifetimes, and thus there is the potential to consider the management of some risks (e.g. equipment) as part of upgrades rather than through designing for future climates. However, there may still be cost-effective actions for critical digital infrastructure, given the cost of downtime from failures is often high; evidence from companies that report that the cost of downtime could be as high as £thousands per minute (Ponemon Institute, 2016).

Warmer temperatures are likely to mean higher cooling needs and associated energy costs (Lee *et al.*, 2013; Capozzoli and Primiceri, 2015; Song *et al.*, 2015). There are a range of adaptation options from early warning and emergency planning through to back-ups to address heat extremes. These issues are linked to the general increase in cooling demand (see Chapter 5: Kovats and Brisley, 2021) and the potential role for energy efficiency standards.

The consideration of network risks, and more focused adaptation strategies to key vulnerabilities, can be a more efficient use of available adaptation resources. Adaptation can also be achieved by enhancing network redundancy and introducing back-ups. Pant *et al.* (2020) investigated the economic impacts of failure events in the telecoms network and estimated that direct losses for the top 50 events could vary between £220,000–£3.6 million/day and total losses vary between £0.34–£7.0 million/day. However, as the degrees of connections are increased, the economic impacts were found to decrease. The authors also show the benefits of introducing backup supply for the electricity sector in delaying and thereby decreasing the disruptions in the ICT sector by up to ~90% compared to a scenario with one connection and no back up (though note the study does not assess costs, and thus the overall economic net benefit).

It is also highlighted that ICT and digital solutions can help reduce risks or realise opportunities in other sectors, i.e. they have considerable potential as part of adaptation across many areas (ITU, 2014).

#### 4.14.3.3 Overall urgency scores (I13)

Further investigation is needed to assess how climate change will affect the frequency and magnitude of interruptions to digital services across the four countries of the UK and whether more action is needed. While National adaptation programmes acknowledge the risks to the digital sector, there is no evidence of specific actions to ensure the resilience of digital infrastructure to the specific hazards of high and low temperatures, high winds and lightning.

**Table 4.56** Urgency scores for risks to digital from high and low temperatures, high winds, lightning

Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further investigation	Further investigation	Further investigation	Further investigation
Confidence	Low	Low	Low	Low

#### 4.14.4 Looking ahead (I13)

Data are not available to assess the vulnerability of the telecoms, digital and ICT sector to climate risks, though actions should reduce the vulnerability of some assets. A useful indicator would be to monitor the number of weather and climate related disruptions across the sector. There is also limited information on the location of UK ICT infrastructure, making it difficult to make a rigorous and quantitative assessment of risks to ICT networks and services. The ownership of a large proportion of ICT infrastructure, particularly data centres, base stations and network connections are spread across the private sector. Information on location and connectivity is not publicly available, for commercial or security reasons, and so it is difficult to assess their potential exposure to extreme events. Improved data availability and sharing would allow the creation of digital twin ecosystems, which would aid in identifying exposure and vulnerabilities. However, it is essential to highlight the pivotal role that digital infrastructure has in underpinning the operation of most other forms of infrastructure, and this role is likely to increase in the future. It is therefore imperative that the resilience of ICT to climate impacts is further scrutinised to mitigate interacting risks across the infrastructure sector.

### 4.15 Case Study - Toddbrook Reservoir

In light of current climate change projections, the periodicity of flood events continues to change significantly. The last independent review, commissioned by DEFRA, used UKCIP02 data and concluded that to a 2050s time horizon that no regional pattern of risk to reservoirs (from climate change) was evident (Defra, 2002). The incident at Toddbrook, although providing a stark reminder of the potential implications of a dam failure, in itself does not change this view, but does demonstrate that a new review based on the latest climate projections is overdue, as is engagement with Adaptation Reporting Power requirements by infrastructure owners. Overall, the incident underlines the need for a watching brief on the future impacts of climate change on dam infrastructure, particularly in light of ongoing maintenance regimes which need to be specifically tailored to the dam type and age.

Designed to supply water to the Peak Forest and Macclesfield Canals, the Toddbrook reservoir, located in the Peak District, hit the headlines in 2019 after heavy rain over a 6 day period between 27<sup>th</sup> July and 1<sup>st</sup> August, following a period of record summer warmth, caused significant damage to the auxiliary spillway. As a precaution, nearby roads and businesses were closed and 1500 residents were evacuated from the nearby town of Whaley Bridge. Fortunately, an urgent response consisting of a rapid lowering of the water level, accompanied by emergency bolstering of the spillway, was sufficient to avert disaster with residents able to return to their homes 6 days later.

As a result of the incident, an independent review was commissioned by the government to identify what might have led to the damage, whether it could have been prevented or predicted and identify any lessons learned. The report concluded that the most probable cause of the failure was poor design followed by a gradual deterioration / erosion of the slipway via seepage flows, as

a result of intermittent maintenance over the years (Balmforth, 2020). Temporary resilience work commenced in January 2020 to further reinforce the dam and spillway by means of waterproof nibs to prevent seepage flows undermining the spillway. However, a longer-term repair is required, which is estimated to cost in the region of £10m and will take several years to implement (Canal and River Trust, 2020).

The heavy rainfall of August 2019 is yet to be attributed directly to climate change, but it is inevitable that some links will be drawn between increasing levels of precipitation in a changing climate and the stability of aging dam infrastructure. Indeed, the need to keep pace with the impacts of climate change is mentioned in the foreword of the independent report (Balmforth, 2020), as CCRA2 had highlighted a potential risk with this type of dam. The rain that fell during the preceding 6-day period consisted of two rainfall events, the latter (between 30<sup>th</sup> July and 1<sup>st</sup> August) being the most significant and classified as a 1 in 100-year event. Although rare, this needs to be considered in the context that Category 1 dams are currently engineered to withstand a 1 in 10,000-year flood event and therefore rainfall events of this magnitude should not have been a key factor in the failure of the asset. Furthermore, the spillway had coped without issue with previous floods in 1998 and 2007. It had also recently been inspected and declared compliant with current legislation (Balmforth, 2020).

## 4.16. References

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UK Climate Risk  
Independent  
Assessment (CCRA3)

# Technical Report

## Chapter 5: Health, Communities and the Built Environment

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## Key Messages

- **High temperatures are increasingly affecting health and wellbeing, but there has been little progress in addressing the increasing risks from overheating through building standards or incentives to retrofit.** Heatwaves in recent summers (2018, 2019, and 2020) have caused significant impacts on mortality and morbidity, and disruptions to public services (including hospitals, care homes, schools and prisons), particularly in England. The frequency and duration of extreme heat episodes is very likely to increase, and high temperatures are likely to exceed tolerance thresholds for many systems. There is more evidence since CCRA2 about the risks of overheating in buildings and the effectiveness and limitations of strategies for passive and space cooling. The installation of passive measures through retrofit are likely to be sufficient to address overheating risks in all regions except London under high rates of warming. However, there is still little preventative action being taken to address health risks from overheating in new or existing homes. Housing policies to address Net Zero may increase the risk of overheating and there is a need to tackle the full range of housing interventions (mitigation, damp, flooding, overheating) in a holistic manner. There is better understanding of the effectiveness of health protection strategies, particularly for actions linked to heat alerts. [Sections 5.2, 5.13, 5.14, 5.15.2, 5.15.3]
- **Flood risk to people from rivers, surface water and coastal flooding remains a high magnitude current and future risk across the UK. Advances have been made since CCRA2 in flood risk management policy, investment and adaptation action, though challenges remain in relation to understanding the resilience of development on the flood plain, limited mandatory management of surface water flooding in parts of the UK and the low take up of Property Flood Resilience.** The majority of the total present and future flood impacts are in England with its larger population, but economic impacts on a per capita basis (Expected Annual Damage per person) are higher in Northern Ireland, Scotland and Wales. Risk of flooding from rivers is the dominant source in terms of annual damages, but assuming that current levels of adaptation continue, surface water and coastal risks increase their relative contribution to UK flood risk. Groundwater flooding continues to have a limited contribution at national scale, although will be important locally. Considerable advances have been made regarding the strategic management of flood risk at national and local levels since the last CCRA, and whilst flood events have occurred, a larger number of properties have been protected than affected. However, it remains unclear how far current policy ambition will go towards keeping future risk constant at today's levels as the climate changes, particularly in relation to improving and monitoring uptake of green sustainable urban drainage and Property Flood Resilience measures, ensuring access to insurance, and avoiding lock-in from development in high flood risk areas. Our assessment is that more action continues to be needed across the UK to address these issues. [Section 5.3, 5.15]
- **Sea level rise and coastal change are likely to threaten the viability of some communities in the future. Some evidence of the vulnerability of specific communities in the South and East coasts of England and the West coast of Wales is already available, but there remains no long-term assessment of viability across the UK.** UKCP18 projections suggest greater sea

level rise than had been projected previously. Considerable work has been conducted to enhance both an understanding of coastal risk and policy and strategy development, particularly at the national level. The example of Fairbourne in Wales is the UK's first community whose long-term viability is unlikely to be sustainable due to sea level rise. Whilst Shoreline Management Plans include long-term strategies to manage coastline in England, Wales and parts of Scotland, there is limited evidence of national and local governments and other stakeholders taking a long-term strategic approach to identify and support communities at risk of loss across the UK. [Section 5.5, 5.15]

- **Higher rates of warming may lead to interruptions of household water supplies which would have health, social and economic impacts, particularly for vulnerable households.** Parts of the UK, particularly in South East England, are already water stressed. Private water supplies are most vulnerable to current and future climate hazards that affect water quality (contamination with pathogens or chemicals) and quantity (interruption of supply). Climate change may increase the risk of contamination of drinking water through increased runoff and flooding events, and additional actions will be required to maintain water quality standards. [Section 5.11]
- **The physical and mental health benefits of increased physical activity and contact with nature are well established, but there is limited evidence on the extent to which a warmer climate is likely to increase these activities.** Policies to promote access to greenspace have been developed at local level and national levels. There remains a lack of research into the opportunities for public agencies to increase outdoor activities for health and wellbeing. [Section 5.3, 5.12]
- **The burden of ill-health from cold weather and cold homes remains significant in the UK and is a priority for public health and local government action.** Climate change is likely to reduce the burden of cold-related mortality, however, the overall burden remains high, even to the end of the century. Population ageing is likely to offset some of the benefit from warmer winters for cold-related mortality. [Section 5.3, 5.7]
- **Climate change may increase damage to homes through increases in subsidence, increases in damp/excess moisture, and increases in structural damage due to high winds.** The presence of at least some relevant building standards across all four UK countries means that the present-day risk is being considered for new build homes or those undergoing refurbishment. However, there is little evidence that the future risks from climate change are being integrated into planning, building design or retrofit, potentially locking in homes to some future risk. [Section 5.5]
- **Climate change will reduce future household energy costs in winter. Cooling demand in summer is likely to increase with climate change if there is significant uptake of mechanical cooling methods (air conditioning).** For this combination of opportunity and risk, government intervention is important for managing energy costs for summer cooling, as well as the reduction in winter heating. Climate change is not yet being factored into government policies in future energy demand sufficiently; including in relation to the scale

and type of energy efficiency, and low carbon heating measures needed to achieve Net Zero. [Section 5.1, 5.6, 5.15.3]

- **Climate change may interfere with efforts to control outdoor air pollution, and ground-level ozone may increase under some high emissions pathways.** Policies to achieve Net Zero are likely to reduce emissions of key outdoor air pollutants and pollutant precursors but not in all scenarios. The impacts on particulate pollution from climate change are highly uncertain and gaps in understanding remain on how future changes in temperature and wind patterns would affect air quality. There is a shortfall in planning for future ground level ozone, pollen, and air pollution caused by wildfire. [Section 5.8]
- **Climate change will increase the risks from vector-borne diseases in the UK.** Lyme disease cases may increase with climate change due to an extended transmission season and increases in person-tick contact. The risk of mosquito-transmitted diseases, such as chikungunya and dengue being present in the UK is likely to increase in England and Wales as temperatures increase. The risk that malaria may become established remains low. The risk of *Culex*-transmitted diseases such as West Nile Virus is likely to increase in the UK. [Section 5.9]
- **Climate change is likely to be an important risk for food safety in the UK.** Foodborne illness has significant health and social costs. Increases in extreme weather patterns, variations in rainfall and changing annual temperatures will impact the occurrence and persistence of bacteria, viruses, parasites, harmful algae, fungi and their vectors. There has been a lack of progress to address current and futures risks from climate change in food systems. [Section 5.10]
- **Climate change may also affect food security in the UK through variability in access to food due to disruptions to the supply chain from climate hazards both in the UK and abroad.** The UK currently is lacking in specific policies to address the implications of climate change for food security. Further action is needed to assess the implications of Net Zero and accessing a sustainable diet but also ensure food systems are resilient to climate change in the future [Section 5.10]
- **Climate change will increase the risk of disruption in health and social care services from floods and heatwaves unless additional action is taken. Disruption to critical services (water, energy, transport) may further undermine the delivery of health and care services.** Impacts will be felt within institutional settings, such as hospitals, residential and nursing homes, and will have negative impacts on health workers as well as patients and residents. Climate change will also have implications for people who receive care services in their own homes. National health systems are developing methods, plans and tools to managing overheating and flood risks, but adaptation is still largely seen as being addressed by emergency planning. The fragmentation of public services could hinder future action, particularly in health and social care. Further action is needed in particular to address overheating in hospitals and residential care buildings. [Section 5.1, 5.2, 5.13, 5.15]

- **Climate change is likely to cause disruption to education and prison services unless additional action is taken.** There is evidence of planning and guidance in line with future climate scenarios being developed in England and Wales, particularly for managing overheating. However, further adaptation measures are essential in each nation to avoid lock-in with building designs and to be resilient to the future risks of overheating, flooding and other climate hazards. [Section 5.14]
- **Coastal heritage is particularly at risk from climate change and heritage organisations and communities may need to accept the loss of some heritage assets, particularly on the coast.** The potential risks and opportunities from climate change for both intangible and tangible cultural heritage are numerous and include the potential to discover previously unknown heritage. There is evidence of a large amount of progress in the heritage sector since CCRA2 to assess risks and adaptation strategies. Continued monitoring is essential to inform risk management and cultural loss needs to be incorporated into adaptation and resilience thinking. [Section 5.12]
- **Housing and planning policies do not sufficiently consider climate change which could create significant lock-in for many different building types.** Current and future adaptation action for health, communities and the built environment has several common challenges and limitations. There is a lack of incentives for retrofitting existing properties. There is a lack of implementation of effective strategies that require changes in behaviour, and some surveys of exposed groups show low levels of awareness of their own risks from climate hazards. [Section 5.1, 5.4, 5.5, 5.15]
- **The effects of the COVID-19 pandemic are likely to place great strain on the health service for some years to come,** even once the pandemic has passed, making capacity to address climate change more limited. [Section 5.12, 5.15]
- **There are synergies and opportunities to address adaptation and mitigation at the same time.** Achieving Net Zero may make adaptation action harder to achieve for some risks, particularly for addressing overheating in buildings. Many Net Zero strategies have the potential to bring significant co-benefits in terms of population health and wellbeing. [Section 5.15]



**Table 5.0.** Urgency scores for risks and opportunities to health, communities and the built environment

Risk number	Risk/Opportunity description	Urgency scores			
		England	Northern Ireland	Scotland	Wales
H1	Risks to health and wellbeing from high temperatures	More action needed  (High confidence)	More action needed  (Low confidence)	More action needed  (Low confidence )	More action needed  (High confidence)
H2	Opportunities for health and wellbeing from higher temperatures	Further investigation  (Low confidence )	Further investigation  (Low confidence)	Further investigation  (Low confidence )	Further investigation  (Low confidence )
H3	Risks to people, communities and buildings from flooding	More action needed  (High confidence)	More action needed  (High confidence)	More action needed  (High confidence)	More action needed  (High confidence)
H4	Risks to the viability of coastal communities from sea level rise	More action needed  (High confidence)	Further investigation  (Low confidence)	More action needed  (High confidence)	More action needed  (High confidence)
H5	Risks to building fabric	Further investigation  (Medium confidence)	Further investigation  (Low confidence)	Further investigation  (Medium confidence)	Further investigation  (Medium confidence)
H6	Risks and opportunities from summer and winter household energy demand	More action needed  (High confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
H7	Risks to health and wellbeing from changes in air quality	Further investigation  (Medium confidence)	Further investigation  (Medium confidence)	Further investigation  (Medium confidence)	Further investigation  (Medium confidence)
H8	Risks to health from vector-borne disease	More action needed  (High confidence)	Further investigation  (Low confidence)	Further investigation  (Medium confidence)	Further investigation  (Medium confidence)
H9	Risks to food safety and food security	Further investigation  (Medium confidence)	Further investigation  (Medium confidence)	Further investigation  (Medium confidence)	Further investigation  (Medium confidence)

H10	Risks to water quality and household water supplies	Further investigation  (Medium confidence)	Further investigation  (Medium confidence)	Further investigation  (Medium confidence)	Further investigation  (Medium confidence)
H11	Risks to cultural heritage	More action needed  (Low confidence)	More action needed  (Low confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
H12	Risks to health and social care delivery	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
H13	Risks to education and prison services	More action needed  (Medium confidence)	More action needed  (Low confidence)	More action needed  (Low confidence )	More action needed  (medium confidence )

## 5.1 Introduction

### 5.1.1 Scope of this chapter

This chapter summarises the evidence regarding the key risks and opportunities of climate change for the UK population, with a particular focus on health and wellbeing, and on the built environment. The chapter covers all UK populations, and risks are assessed separately for England, Wales, Scotland and Northern Ireland. The chapter addresses how climate change risks are likely to vary by type of settlement (urban, rural, coastal) as well by geographic region. Risks to (or managed through) the built environment apply to all communities and not just urban areas. We also consider whether the health impacts of climate change will affect some groups more than others, particularly those who are more vulnerable due to low incomes, age or disability.

The evidence in this chapter is divided into **13 climate risks and opportunities**. These encompass a wide range of policy areas: communities and planning; buildings and cultural heritage; the health system, the social care system; education and prisons. Some upstream policy issues are addressed in other chapters. It is important to note that many of the wider (environmental and social) determinants of the health of the UK population are governed by ‘non-health’ government departments. (Table 5.1)

For each risk and opportunity, the assessment is divided into three parts as set out in Chapter 2 (Watkiss and Betts, 2021), an assessment of current and future risk or opportunity in the absence of further adaptation, an assessment of how far planned adaptation will manage the risk or opportunity, and the benefits of further action in the next five years.

The assessment of the magnitude of current and future risks follows criteria outlined in Chapter 2 (Watkiss and Betts, 2021), including that a range of climate scenarios must be considered spanning a 2°C increase in global temperature by 2100 (the low climate scenario), up to global temperatures reaching 4°C between 2070 and 2100 (the high climate scenario). Magnitude of risks are assessed for a diverse range of outcome measures. Few studies have quantified the impact of climate change on health or social outcomes or have estimated the economic (damage costs) of the future impacts, therefore the assessment relies on expert judgement for some risks. The magnitude of impacts from climate hazards is often estimated as annualised damages, but the impacts of extreme events or singular events (e.g. disease introduction) are also considered. Many climate-related risks are already being well managed, but climate change may still cause a ‘climate penalty’ so that the reductions in risk are less than they would be without climate change. There is very little information on health impacts of climate-driven low likelihood, high magnitude events and these are not included in the magnitude scoring (see Box 5.1).

**Table 5.1.** Responsibilities for adaptation by government department for each nation\*.

Policy area	England	Northern Ireland	Scotland	Wales
Housing and urban planning	Ministry of Housing, Communities & Local Government	Department for Communities	Local Government and Community Development	Department of Housing and Local Government
Transport	Department for Transport	Department for Infrastructure	Transport Scotland	Transport for Wales
Education	Department for Education	Department of Education	Education Scotland	Department for Education & Skills
Justice and prisons	Ministry of Justice	Department of Justice	Justice Directorate	Ministry of Justice
Employment regulations and protections	Department for Business, Energy & Industrial Strategy	Department for the Economy	Business, Fair Work and Skills Directorate	Directorate for Social Partnership & Fair Work
Social protection measures	Department for Work and Pensions	Department for Communities	Social Security Scotland	Directorate for Social Partnership & Fair Work
Hazard regulation in the environment (e.g. flood risk management, regulation of chemical and microbiological hazards in the air, water and soil)	Environment Agency, Department for Environment, Food & Rural Affairs	Department for Infrastructure Rivers	Scottish Government, Scottish Environment Protection Agency	Welsh Government, Natural Resources Wales
Cultural heritage	Department for Digital, Culture, Media & Sport, and Historic England	Historic Environment Division (DoC)	Scottish Government, Historic Environment Scotland	Welsh Government, Cadw

\*Health and public health agencies not included.

#### **Box 5.1. Low Likelihood High Impact events (LLHI): Health, Communities and the Built Environment**

Communities are exposed to infrequent high magnitude events. The National Risk Register (HM Government, 2020b) considers the plausible risks (climatological and technological) that can cause major harm (deaths) or seriously disrupt security in the UK. These risks do not consider the most extreme climate changes, such as the climate system tipping points and abrupt climate change described in Chapter 1 (Slingo, 2021).

This chapter considers low likelihood high impact events in terms of the catastrophic outcomes (rather than the climate causes of LLHI). Catastrophic outcomes are likely to occur when there is an extreme climate event in combination with a failure or extreme event in the human system. Very high rates of global warming, such as in climate scenarios based on RCP8.5-level emissions and/or climate models with very high climate sensitivity, would bring greater risks to health and security than those estimated under the scenario of 4°C global warming by 2100.

The most potentially catastrophic climate ‘event’ risks for the UK are major coastal and river flooding. These risks are considered explicitly in Risks H3 and H4. Loss of life would be caused by a sudden failure of defences and factors that inhibited evacuation measures such as failures in warnings, damage to roads, etc. Similarly, a storm surge leading to significant coastal erosion and loss of land could impact coastal communities. Coastal erosion is notoriously difficult to predict, with recent events including a 10 metre loss from a single storm event at Formby, Sefton in December 2013, and 12 metres from a single storm in February 2002.

Sudden failures of key infrastructure have the potential to cause major loss of life (see Chapter 4: Jaroszweski, Wood and Chapman, 2021), including releases of harmful chemicals or radioactive materials from industrial installations (H10). The near failure of the Toddbrook Reservoir and potential fatalities in the town of Whaley Bridge is discussed in detail in the Case Study in Chapter 4 (Jaroszweski, Wood and Chapman, 2021). Sudden slope failures can be triggered by heavy rainfall, and have the potential for large loss of life (such as the Aberfan disaster in 1966). Wildfires are also recognised risks in the National Risk Register and are an increasing threat in the UK (Box 5.4).

After mid-century the risk of water shortages in the South East of England becomes more apparent in the CCRA3 projections. A failure of the water supply in a densely populated area would have serious consequences both locally and nationally.

### 5.1.2 Social, technological and economic trends that affect risks and adaptation

Social and economic trends are highly relevant to the impacts of climate change, and strongly influence the future magnitude of risks (See Chapter 2: Watkiss and Betts, 2021). These trends are relevant not just for the populations that may be affected by climate change, but will also reflect the capacity for adaptation action (at national and local level). Climate and socio-economic factors can act together as risk multipliers, although for some changes, socio-economic change can reduce vulnerability and thus reduce the absolute burden on health of climate hazards.

Some of the major trends are described here and summarised in Table 5.2. These are also discussed in more detail under each risk.

The UK population is increasing and ageing, and these trends are projected to continue (Figure 5.1). Population growth and age distribution estimates are updated regularly by ONS. There are major uncertainties about future immigration policies (from Europe, post EU exit, and also from non-European countries) and immigration is an important determinant of future population size. There have been few assessments of future population distribution within the UK, particularly differences in regional population growth, and urbanisation. It is too early to know if the COVID-19 pandemic has affected population distributions within the UK, particularly the movement of people from inner cities to suburban and rural locations, and whether this is likely to be maintained long term (beyond 2050).

**Table 5.2.** Summary of UK future trends and policies that affect the magnitude of risks and/or the capacity to adapt.

	<b>Heat-related risks [H1, H2, H6]</b>	<b>Flood-related risks [H3, H4, H5]</b>	<b>Biological and chemical hazards [H3, H7, H8, H9, H10]</b>	<b>Cultural heritage [H11]</b>	<b>Delivery of key services [H12, H13]</b>
<b>Factors affecting magnitude of risks</b>					
Population growth	Population growth increases population at risk	Drives targets for new build houses. Population growth increases population at risk of flooding by increasing demand for housing.	Increases exposure of population at risk	May increase visitor pressures on cultural heritage sites, but also income	
Population ageing	Increases in older age groups who are most vulnerable to extreme weather	Increases in older age groups who are most vulnerable to extreme weather		Potential need to improve accessibility to historic sites and buildings with an older population	Increases in population vulnerable to extreme weather. Increased demand for services.
Economic growth	Costs to households and economy. Growth will increase income for retrofitting measures	Costs to households and economy. Growth will increase income for Property Flood Resilience measures and insurance	Costs to households and economy	May increase income to help with adaptation implementation	Costs to public sector and economy. May increase income to help with adaptation implementation
<b>Key barriers and facilitators of adaptation</b>					
Urban development (urban expansion)	Increased urban density increases outdoor temperatures (urban heat islands)	May increase population at risk of flooding and reduce green spaces impacting on drainage	May increase exposure to some air pollutants	Potential loss of historic sites and / or buildings	Changes to profile of service delivery
Changes in urban green space	Increases in green space can reduce urban heat islands	Increases in green space can support flood risk management			Opportunities for more outdoor recreation could reduce health burdens
Housing need	Expansion of new build homes that do not account for overheating. Loss of green space (cooling)	Expansion of new build homes in Flood Zone 3. Loss of greenspace			

Changing regulatory standards and legal frameworks (devolved and non-devolved)			Less regulation will increase risk of contaminated food and water, and polluted air		
Changes to public health surveillance systems			Reduced access to ECDC information post EU-exit will impede strategies to control vector borne diseases		Focus on infectious disease management
Fragmentation of (public services)	Organisational barriers to implement coherent strategies	Organisational barriers to implement coherent strategies	Organisational barriers to implement coherent strategies	Organisational barriers to implement coherent strategies	Organisational barriers to implement coherent strategies
Net Zero / decarbonisation policies	See separate table 5.55				

Note: Empty cells indicate lack of significant effect – positive or negative. Adapted from CCRA2 (Table 5.3)

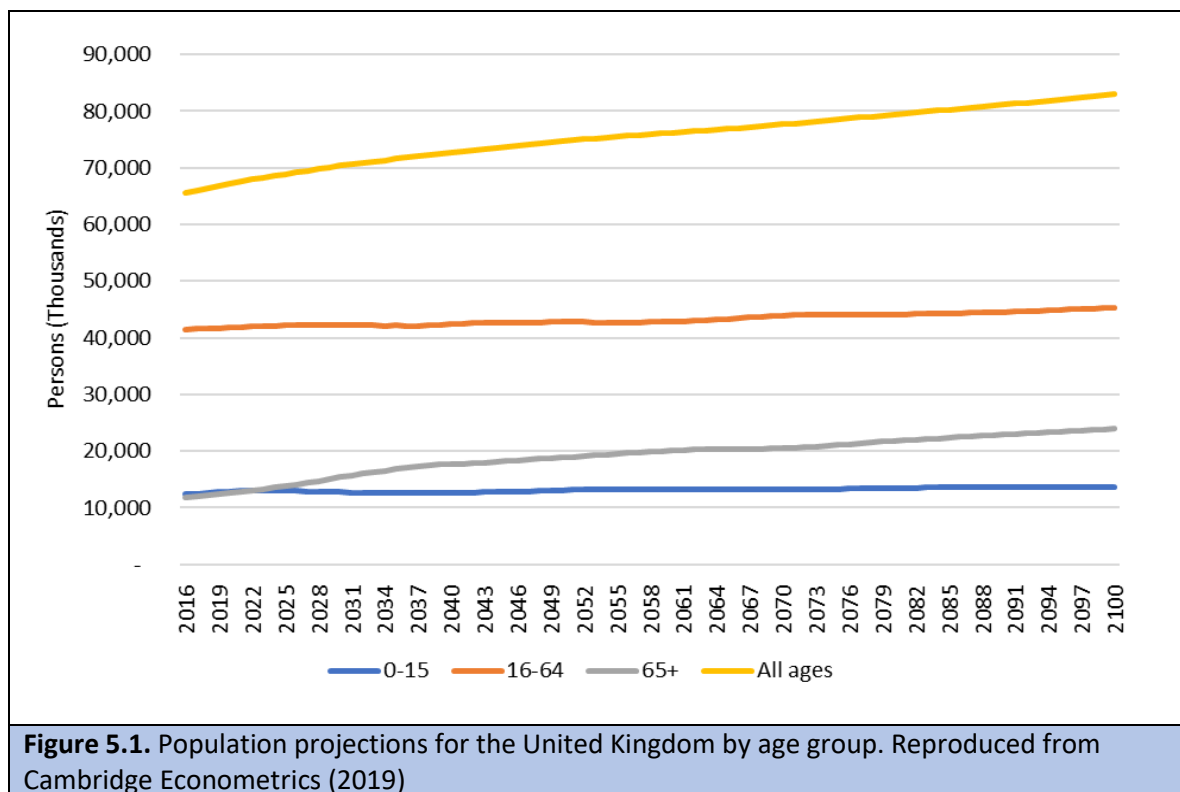
The UK population was estimated to be 66.7 million in mid-2019. The UK population is projected to pass 70 million by mid-2031, reaching 72.4 million by 2043 (ONS, 2020b), with most growth in England. Projections are more uncertain beyond mid century, with long-range projections ranging from 92 million to 66 million by 2100. Population in urban areas, particularly London, is likely to increase. The UK population is ageing, with older people accounting for an increasing share of the total population. By 2100, those aged over 65 are expected to account for around 30% of the total population, compared to 18% in 2016.

The future UK population is projected to be more diverse and more people will be living alone. The number of households may increase by 4 million between 2016 and 2041, and by 14 million to 2100 (compared to 2016). The majority of growth in the number of households is expected to be caused by the ageing population, as the number of households headed by someone aged over 65 increases, and likelihood of single occupancy increases. This has implications for housing demand.

There will likely be an increase in the number of older adults requiring care (people over 75 years with co-morbidities, persons over 85 years). The number of people aged 65 years or older in England is projected to increase significantly (Kingston *et al.*, 2018). Watkiss *et al.* (2019) have estimated that, assuming rates of dependency remained the same, an extra 90,000 more care home places will be needed by 2025 and 190,000 by 2035. There is considerable uncertainty regarding the net economic impact of the ageing population. Older people could be a driver of economic growth and social wellbeing, or place a significant economic burden on the younger working population (Appleby, 2013).

Health and social care systems are likely to evolve over the coming decades, due to government policies as well as advances in technology. It is likely that e-medicine will increase in the future and the current trend of treating people at home rather than in hospitals will continue. There are likely

to be significant changes regarding social care, given rising demand. The COVID-19 pandemic has revealed several limitations in the current social care system that may hasten changes in this sector. The public health system in England was re-organised in 2021 to form the national UKHSA (UK Health Security Agency) to ensure improved response to future pandemics.



The UK Government has stated the ambition to deliver 1.5 million net additions to the housing stock by 2022 (Wilson and Barton, 2021). The number of new homes needed in England is at least 345,000 per year, accounting for both new household formation and a backlog of existing need for suitable (affordable, healthy) housing (Wilson and Barton, 2021).

Building standards for new properties do not take climate change into account sufficiently (see Risks H1, H2, H5, H12 and H13) and so new homes represent 'locking in' risks for health and social costs from climate change. New and existing homes also often do not perform in line with minimum standards of performance expected by law due to issues with knowledge, skills, supply chains, occupant behaviour and quality assurance. Failure to perform in line with standards means locking in cold and damp homes, higher bills and greater risks of flooding for decades (CCC, 2019a).

It is not clear if there will be an expansion in urban areas in the future and if current greenfield sites will be converted to urban or housing developments. National plans (including England's 25 year Environment Plan) have established objectives to protect biodiversity, maintain natural environments and increase urban green and blue space. However, the current trend is that urban green space is declining, particularly green space within current urban boundaries (CCC, 2019b).

Economic growth is an important factor for facilitating climate adaptation, both in relation to what households can afford and also in relation to the level of public spending for key public services. The



current pandemic is having a detrimental effect on the economy and it is not yet clear how long the economic impacts will continue.

At the time of writing, the regulatory standards and legal frameworks (devolved and non-devolved) for air and water quality and food safety are uncertain following the UK's exit from the European Union. The UK will no longer be obligated to implement several key EU Directives for health protection and currently there is no agreement on what will be implemented after the transition period (from 1<sup>st</sup> January 2021) with particular concerns for health regarding food safety and security (Benton *et al.*, 2020). A Health Impact Assessment by Public Health Wales described mechanisms by which Brexit may undermine the control of chemical and biological hazards for human health by weakening regulations and responsibilities for polluters (Green *et al.*, 2019) (see Table 5.2). In addition, the EU exit may entail reduced access to data, intelligence and evidence sharing mechanisms (devolved and non-devolved) and reduced access to EU research funding that has been important for improving the evidence based for climate risk management.

There are a range of pathways and specific strategies that can be adopted to achieve Net Zero greenhouse gas emissions; some of these will benefit adaptation, some may impede adaptation if additional action is not taken. Many Net Zero strategies have the potential to bring significant co-benefits in terms of population health and wellbeing. The implications of Net Zero strategies are addressed explicitly in each risk and also summarised at the end of the chapter (Section 5.15.3).

### 5.1.3 Fair adaptation: assessment of the distributional effects of risks and responses

Environmental health inequalities refer to general differences in environmental conditions important for human health and wellbeing. Socioeconomic and demographic inequalities in exposure to environmental hazards exist everywhere and can be expressed in relation to factors that may affect the risk of being exposed, such as income, education, employment, age, sex, race/ethnicity and specific locations or settings. In addition to these differences in exposure, environmental health inequalities are also caused by social or demographic differences in vulnerability/susceptibility towards certain risks. Certain groups may also have differential recovery after an extreme event, and that can exacerbate inequalities when a population is exposed to repeated climate hazards.

Adaptation planning needs to consider who benefits and who is potentially disadvantaged by specific measures. It is well established that certain policies, for example, those that rely on behaviour change, can lead to selective uptake and thereby exacerbate inequalities in health (Marmot *et al.*, 2020). Adaptation policies may therefore require additional effort to ensure that low income households are sufficiently prepared for climate change.

Protected characteristics of individuals and equality of opportunity are those factors covered by the Equality Act 2010 to prevent discrimination, and they include age, gender, race, disability, religion, beliefs and being pregnant. However, discrimination by individuals and organisations is only a part of the wider causes of health and social inequalities. Structural causes of inequalities are manifested in terms of differences in access to housing, income, employment, and basic services. Thus, opportunities for adaptation are unlikely to be evenly distributed across the UK population.

The UK has a geographically unequal developed economy, and this is reflected in differences in health/wellbeing indices like life expectancy between high and low income locations (ONS, 2019). The gap between economic growth in London and the South-East and other regions has increased: between 2006 and 2016, London was the only region to improve its position relative to the UK average. However, differentials in household income across the UK are more complex, and also the relationship between household incomes and wellbeing. The South West of England and Northern Ireland ranked the highest for personal well-being indicators such as life satisfaction, feeling worthwhile and happiness. Urban areas in the South East area of England are among the most productive and economically prosperous places in Europe, but areas in the North and Midlands and the Southwest are the least economically prosperous in the UK. The Government has policies to address this inequality through infrastructure development, and investment in education, skills and scientific R&D.

Local and neighbourhood issues are also important for health and wellbeing. In England, deprivation is widely distributed (61% of local authority districts contain at least one of the most deprived neighbourhoods in England). However, Middlesbrough, Liverpool, Knowsley, Kingston upon Hull and Manchester are the local authorities with the highest proportions of neighbourhoods among the most deprived in England. Deprivation is measured by ONS using Indices of Deprivation based on census data (ONS, 2019). Areas with high deprivation in Scotland include those in Inverclyde, Glasgow City, North Ayrshire, West Dunbartonshire and Dundee City. In Wales, there are locations of high relative deprivation in the South Wales cities and valleys, and in some North Wales coastal and border towns (Statistics for Wales, 2019). Northern Ireland has higher levels of multiple deprivation than the rest of the UK, with locations of high relative deprivation in urban areas of Belfast and Derry City and Strabane (NISRA, 2017).

The distributional aspects of climate change (who is most affected) are discussed within each risk, and how this may change over time. For most risks, the most affected groups vary geographically, by local neighbourhood factors, and by individual characteristics (age, gender, household income, housing tenure). For many risks, particularly flooding and heatwaves, low income households are likely to be more affected in terms of health impacts (Table 5.3). Poor households will also bear a disproportionate burden of the the social and economic costs of extreme weather. However, it is worth stressing that these risk differentials are currently not large. All populations will be affected by climate change. The impacts of climate change will not be confined to poorer locations.

The Marmot Report (Marmot *et al.*, 2020) promotes two strategies to reduce inequality in the UK: consideration of equality and health equity in all policies (across the whole of government, not just the health sector) and effective evidence-based interventions and delivery systems. Adaptation strategies and measures need to be evidence based and promote equity – that is, to not disadvantage particular groups or individuals. The evidence regarding the equity implications of adaptation options are discussed within each risk. There are some strategies that have a particular risk of disadvantaging poorer households, such as insurance and housing interventions (Table 5.3).

**Table 5.3.** Dimensions of inequality that are reviewed in this chapter in relation to the risks and responses

Category of disadvantage	Impacts of climate hazards (current and future)	Impacts of intervention and policy measures
Individual factors <ul style="list-style-type: none"> <li>• Age (older people, children)</li> <li>• Gender</li> <li>• Race and ethnicity</li> <li>• Pregnant women</li> <li>• People on low income</li> <li>• People with disabilities</li> <li>• Housing tenure (e.g. private renters)</li> <li>• Other</li> </ul>	Who is flooded – distribution of flood exposures.  e.g. High income households more likely to be affected by river flooding; Low income households more ‘at risk’ of coastal flooding.  Who is most affected by floods.  Little evidence that there is a socio-economic gradient in the impact of heat on mortality.	Flood risk management and selective retreat in coastal populations.  Retrofitting of dwellings less affordable for poorer households. Risks for private renters.  Air conditioning and energy costs affordable for more affluent households
Local/neighbourhood factors. <ul style="list-style-type: none"> <li>• Urban poor</li> <li>• Poor coastal communities/seaside towns</li> <li>• Rural poor</li> </ul>	Deprived communities may be more risk of coastal flooding.  Inequalities in access to emergency responders during flooding  Deprived communities in urban areas are less likely to have access to green space.	Investment in public services.  Engagement and community involvement in coastal management plans.  Spatial planning to reduce urban heat islands.
Wider inequalities within the UK <ul style="list-style-type: none"> <li>• England (North vs South)</li> <li>• Northern Ireland (East vs West)</li> <li>• SW and Cornwall</li> <li>• Islands in Scotland</li> </ul>	Geographical remoteness means that communities are more dependent on transport and ICT infrastructure.	Regional priorities for investment for infrastructure and local government funding.

## 5.2 Risks to health and wellbeing from high temperatures (H1)

High temperatures affect a very wide range of health, wellbeing and social outcomes. England experienced heatwaves in 2018, 2019 and 2020 which caused significant excess mortality. There has been increased understanding of the impacts of heat other than acute mortality. Public health activities to prevent heat risks to health have been evaluated and shown to be largely effective for preventing deaths on the hottest days. The risks from combined exposures from heat, air pollution, drought and wildfires are increasingly recognised.

Temperatures have increased in the UK and are higher than have been experienced previously. A new UK record for maximum daily temperature of 38.7°C was set during a brief but exceptional heatwave in July 2019. All the top 10 warmest years for the UK in a series from 1884 have occurred since 2002. Temperatures are projected to increase significantly, particularly in the scenarios with higher emissions (Chapter 1: Slingo, 2021).

There is more evidence about the risks of overheating in buildings and the effectiveness and limitations of strategies for space cooling. There have been improvements in how to design buildings

and use technology that could deliver homes which have high levels of thermal efficiency (staying warm in winter while cool in summer), while being moisture-safe and with safe levels of indoor air quality.

There is still little preventative action being taken to address health risks from overheating in buildings. In England, it has been estimated that 20% of homes are at risk from overheating. The Ministry of Housing, Communities and Local Government (MHCLG) published a consultation in 2021 proposing to introduce an overheating standard in new residential buildings (including houses, flats, care homes, and residential educational settings) as part of the Future Buildings Standard (MHCLG, 2021). The Welsh Government have proposed something similar for dwellings. If brought into policy these changes would help tackle the risk of overheating in new buildings in England and Wales. For existing dwellings, there remains little incentive to retrofit adaptation measures to reduce overheating across the UK.

The potential benefits of higher temperatures are considered in Risk H2 'Opportunities for health and wellbeing from higher temperatures', together with the benefits from reduced exposure to cold. Heat is a widespread risk that affects many sectors, and there is consideration of heat (particularly overheating and indoor temperatures) in other risks in this assessment: H12, Risks to health and social care delivery; H13, Risks to schools and prisons; and B6, Risks to business from reduced employee productivity due to infrastructure disruption and higher temperatures in working environments.

## 5.2.1 Current and future level of risk (H1)

### 5.2.1.1 Current risk (H1)

#### 5.2.1.1.1 Current risk – UK wide

All areas in the UK have experienced warmer summers and milder winters, consistent with global trends (see Chapter 1: Slingo, 2021). The number and length of heatwave events have increased throughout the UK (Sanderson *et al.*, 2017). England has experienced heatwaves of public health importance in 2018, 2019 and 2020 which were associated with significant impacts on daily mortality. There is also more evidence regarding the non-fatal impacts of heat on maternal health, mental health and occupational health.

Several systematic reviews of heat-health studies have been published since the CCRA2. The impact of high temperatures on acute mortality (daily deaths) is very well described with all populations showing that the risk of acute mortality increases at high temperatures (Guo *et al.*, 2018). Hajat *et al.* (2014) estimated that there are 2,000 heat-related deaths per year across the UK. This estimate is supported by a more recent analysis of nation-wide estimates of temperature-mortality relationships which also shows little change in the effect estimates over time (Williams *et al.*, 2019).

High temperatures have a range of impacts on health and wellbeing that affect all ages:

- Maternal health: High temperatures can adversely affect the health of pregnant women, particularly increasing the risk of preterm birth (Chersich *et al.*, 2020).
- Mental health: There is a lack of evidence of impact on mental health effects, although there is some evidence that high temperature can worsen symptoms, and there is some evidence that high temperatures increase the risk of suicide (Thompson *et al.*, 2018).
- Unintentional Injury and accidents: There is good evidence that high temperatures can increase the risk of injury, particularly injuries in children (Otte im Kampe *et al.*, 2016).
- High temperature can impair labour productivity and lead to heat injuries and accidents in workers (Binazzi *et al.*, 2019) (see risk B5 in Chapter 6: Surminksi, 2021).

These studies are relevant for all populations in the UK. The sections below describe observed impacts and projected impacts that are specific to the national populations, although this evidence is limited.

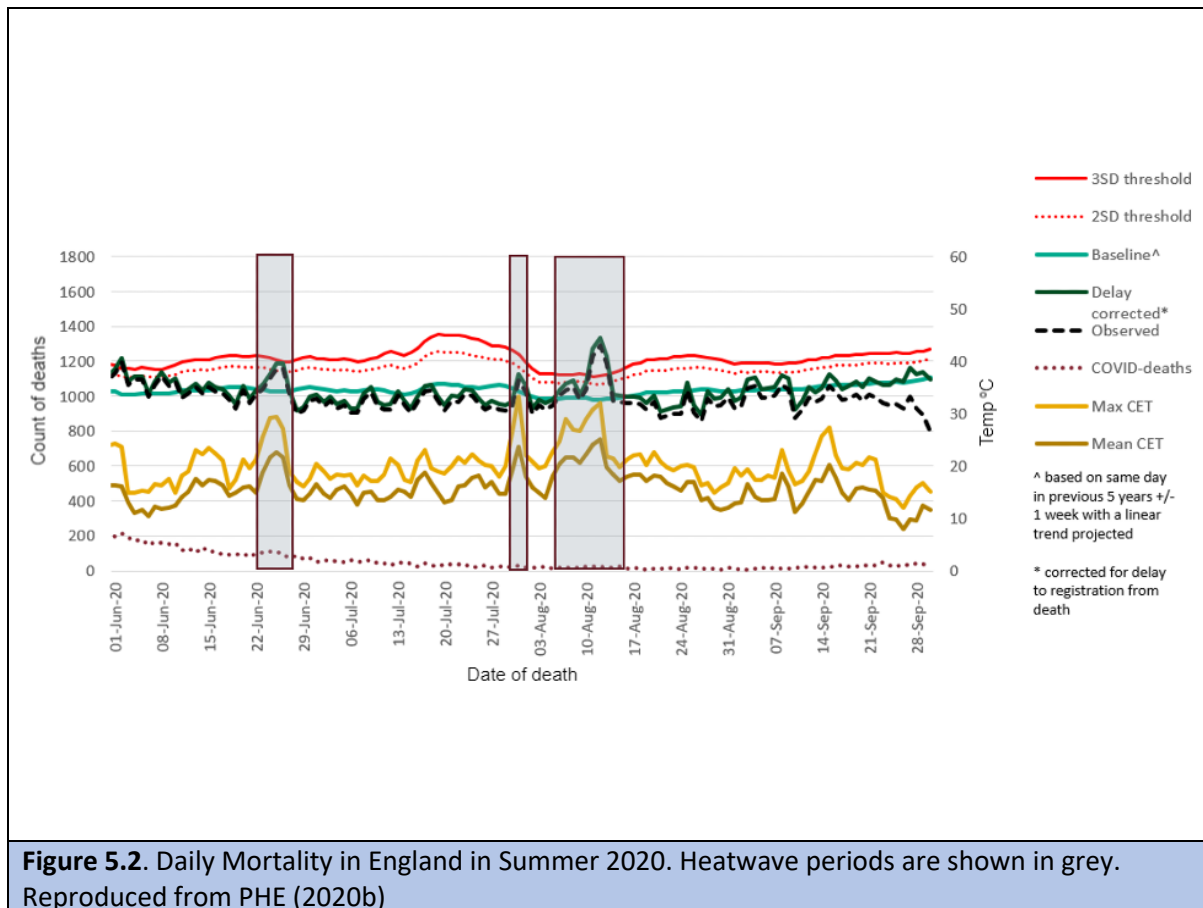
There has been more research to characterise urban heat islands for individual cities but a comprehensive UK-wide assessment on urban heat islands has not been published.

#### 5.2.1.1.2 Current risk in England

There is more information since CCRA2 about the impacts of heatwaves in England. England has experienced severe hot weather episodes in 2018, 2019 and 2020. Public Health England reports regularly on mortality attributed to heatwaves (PHE, 2020b).

- **2018:** England experienced four heatwaves (three Level-3 heatwave alerts and one heatwave where the mean Central England Temperature (CET) was greater than 20°C). The total impact over the summer 2018 period was 863 deaths, with impacts highest in the London region. A period of high temperature in spring (April 2018) was also associated with a mortality excess but analyses of this has not yet been published. The air quality was low in 2018, particularly with high levels of ground-level ozone (see Risk H7).
- **2019:** England experienced three heatwaves (two Level-3 heatwave alerts and one heatwave when mean CET was greater than 20°C). The estimated impact was 892 excess deaths over the summer 2019 period. There is evidence of an excess in the 0-64 year age group for the heatwaves in 2019 at the regional level (in London and the West Midlands).
- **2020:** England experienced three heatwaves in July and August. The total cumulative all-causes all-ages excess mortality was 2,556 (taking out the effects from COVID-19), with the majority of deaths in the 65+ age group (2,244 deaths) (Figure 5.2). Statistically significant excesses were observed in all regions of England, except for the North East and Yorkshire and the Humber, but impacts were greatest in London and the South East.

The impact on mortality in 2020 was much greater than in previous years, and comparable to that observed in England during the 2003 pan-European heatwave (2,234 deaths) and 2006 heatwave events (2,323 deaths) (PHE, 2020b). The cumulative excess all-cause heatwave mortality in summer 2020 was the highest observed since the introduction of the Heatwave Plan for England in 2004.



The built environment is an important determinant of heat-health risk. Heat risks are a combination of housing factors (indoor temperatures), urban density and heat islands (outdoor temperatures) and individual vulnerability factors. These factors can all help to identify areas of elevated heat mortality risk during hot weather. The impact of urban heat islands and the mapping of ‘hotter’ neighbourhoods have been assessed in London (Wolf and McGregor, 2013; Taylor *et al.*, 2015), Birmingham (Tomlinson *et al.*, 2011) and Sheffield (Liu *et al.*, 2017).

There is new evidence on variations in overheating risks between dwellings of different characteristics. Evidence from both monitoring (Beizaee *et al.*, 2013; Lomas and Kane, 2013; 2015) and building physics modelling (Mavrogianni *et al.*, 2012) studies point to an increased risk of overheating in flats and more energy efficient dwellings. Subsequent studies have confirmed variations in overheating risk between dwellings, isolating characteristics which may increase the risk of exposure to elevated temperatures. There is new evidence regarding the risks of overheating in low energy dwellings (that is buildings specifically designed to have low carbon emissions, such as Passivhaus dwellings (see Net Zero section below) due to increased airtightness and lack of ventilation.

According to large sets of indoor monitored data, the rates of overheating in English dwellings are around 20% (Beizaee *et al.*, 2013; Hulme *et al.*, 2013; Lomas and Kane, 2013) to 26% (Petrou *et al.*, 2019), although this will likely depend on the overheating metric and the weather conditions when the monitoring took place. Overheating has been found to be higher in bedrooms and dwellings that have high levels of insulation which were observed to overheat twice as frequently (Gupta *et al.*,

2019), although the correlation between dwelling characteristics and indoor overheating is complex as loft and wall insulation can also help prevent increased risks by keeping heat out. An analysis of monitoring data collected during the Energy Follow-Up Study (EFUS) found that the main heating system, tenure and occupant vulnerability all had statistically significant associations with indoor temperatures (Petrou *et al.*, 2019). In general, dwellings with higher energy efficiency ratings (Standard Assessment Procedure (SAP) rating >70), those that were built more recently, and those with communal heating had higher summertime indoor temperatures. A modelling study indicated that loft conversions are at particular risk of high temperatures due to their position under a roof and relatively low thermal mass (Li *et al.*, 2019).

Evidence also indicates the key role that occupant behaviours can play in indoor heat exposures. For example, failure to open windows can significantly increase overheating risk in dwellings (Taylor *et al.*, 2018), however a monitoring and questionnaire study found around 70% opened only one or two windows at night in London for security reasons (Mavrogianni *et al.*, 2017). Internal gains – including those from poorly-insulated pipes or ductwork – are also significant sources of indoor heat (McCleod and Swainson, 2017).

Poor indoor environments may contribute to a reduction in work performance in adults (Lan *et al.*, 2011). Occupational risks from high temperatures are still rare under the current climate. The HSE reports work injuries for England but heat injuries were not separately reported. Below the threshold of a demonstrable case of heat injury (heat exhaustion, heatstroke, heat syncope), there are negative impacts on wellbeing and comfort, leading to staff absence and dissatisfaction, as well as directly on productivity. High temperatures can also increase the risk of accidents at work (Otte im Kampe *et al.*, 2016; Binazzi *et al.*, 2019). Occupation heat risks are also of concern for workers in the health/social care sectors (see Risk H12) and prison/educational sectors (see Risk H13).

#### 5.2.1.1.3 Current risk in Northern Ireland

There has been limited epidemiological analysis of the health impacts of hot weather in Northern Ireland. Hajat *et al.* (2014) estimated that in 2020 there would be around 1.6 heat-related deaths per 100,000 population (which with a population of 1.89 million equates to approximately 30 heat-related deaths per year).

Evidence from studies on housing indicates that some dwellings are at risk of overheating (Porritt *et al.*, 2012) but the overall prevalence of overheating risk is unknown. An observational study in four NI dwellings found that retrofitting for energy efficiency did not increase the risk of overheating (McGrath *et al.*, 2016) but more research is needed.

#### 5.2.1.1.4 Current risk in Scotland

There is very little evidence of the current impacts of high temperature on mortality and morbidity in Scotland, although it is a reasonable assumption that impacts in southern Scotland may be similar to those observed in northern England.

Hajat *et al.* (2014) estimated that in 2020 there would be around 1.3 heat-related deaths per 100,000 population (which with a population of 5.5 million equates to approximately 70 heat-related deaths per year).

There is limited evidence regarding overheating in dwellings in Scotland. One study estimated that upwards of 54% of new build properties experience overheating in the current climate (Morgan *et al.*, 2017).

#### 5.2.1.1.5 Current risk in Wales

There have been no official reports of the impacts of the recent heatwaves and so the impact on mortality in Wales is unclear. However, Hajat *et al.* (2014) estimated that in 2020 there would be around 3.5 heat-related deaths per 100,000 population (which with a population of 3.15 million equates to 110 heat-related deaths per year).

We have also been unable to identify any studies that look specifically at current overheating in homes in Wales in particular. The Welsh Government commissioned research to assess the risk of overheating of new homes in Wales (using weather data from Cardiff for 2011-2040). This research is discussed below in the future risk section [Section 5.2.1.2.5].

#### 5.2.1.2 Future Risk (H1)

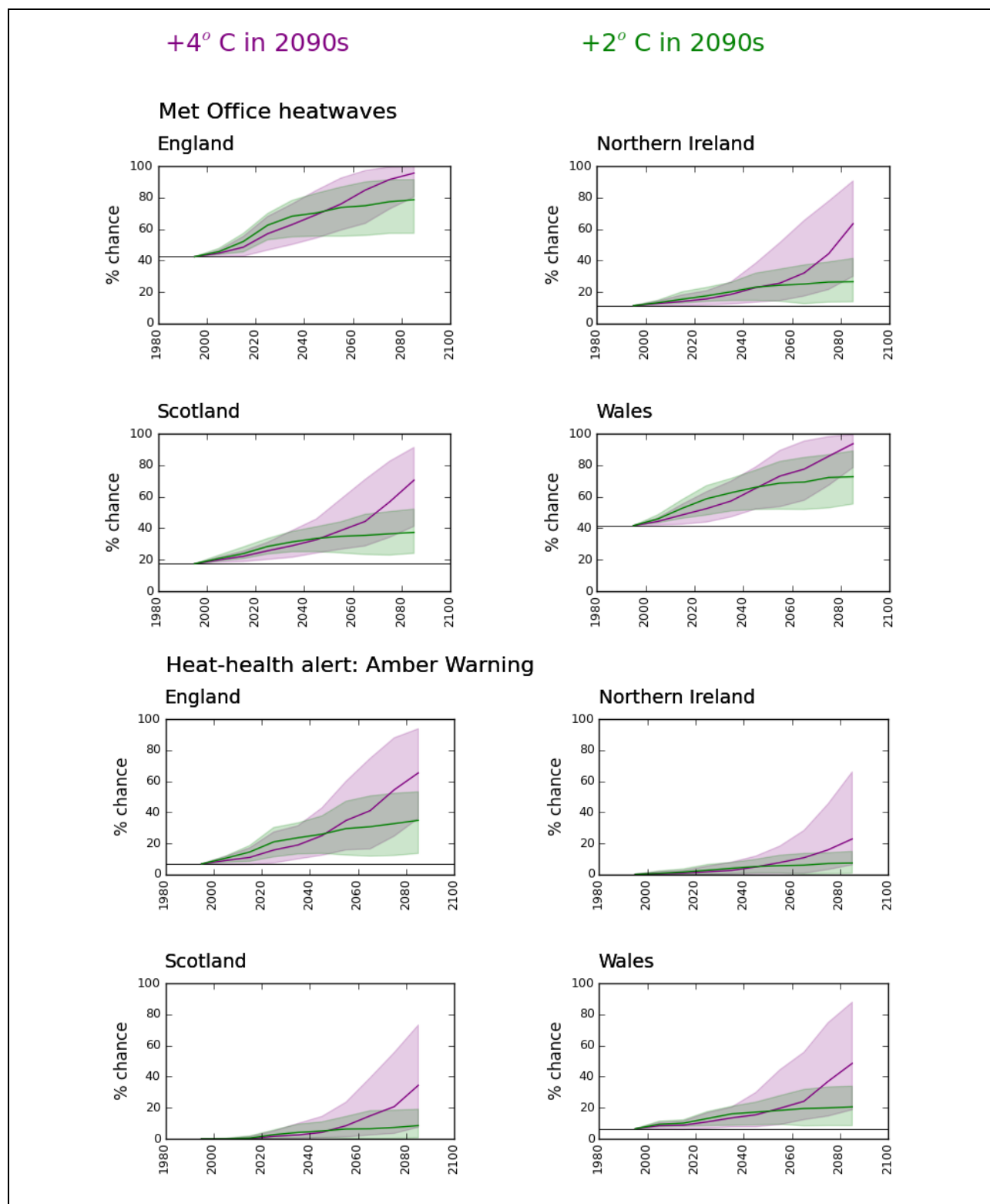
##### 5.2.1.2.1 Future risk – UK

UKCP18 projections for the UK show increases in average summer temperatures and increases in the number of hot days and heatwave events (Chapter 1: Slingo, 2021; Section 1.5.6.) All regions in the UK will experience more frequent and more severe extreme daily high temperatures. These projections includes better representation of the landscape and urban areas including urban heat island effects. There is a very small chance of exceeding 40°C by 2040; by 2080 the frequency of exceeding 40°C is similar to the frequency of exceeding 32°C today. Night-time urban heat island effects are expected to be more intense, leading to more ‘tropical nights’ in major cities.

As temperatures increase, the frequency and intensity of heatwave events is projected to increase (Figure 5.3). The Met Office estimates that a ‘hot’ summer such as 2018 had a probability of approximately 10% in the period 1981 to 2000, which is now somewhere between 10% and 20%, but this will increase to probabilities of the order of 50% by mid-century irrespective of emissions scenario (Met Office, 2019). Therefore, such changes could still occur even with low emissions. The ‘heatwave’ season will increase in length, meaning that heat risks may become significant in early summer and spring. There is currently a regional difference in the impact of heat, with London and the south east experiencing the highest summer temperatures.

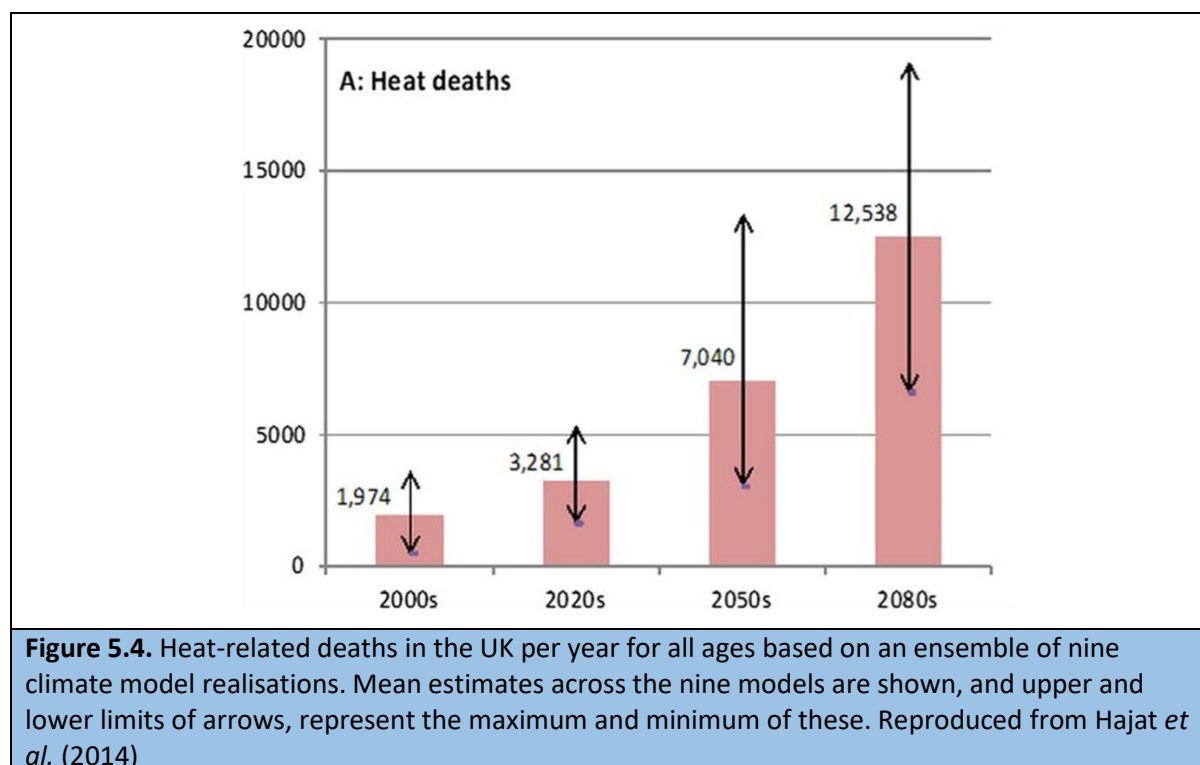
Projections of overheating in buildings (Taylor *et al.*, 2016) modelled the overheating risk in dwellings across Great Britain, find that many of the housing types will be at increased risk of overheating.





**Figure 5.3.** Annual likelihood of at least one heatwave event by country, under UKCP18 projections constrained to pathways to 2°C, and 4°C global warming at 2100. Top. “Met Office Heatwave” events defined as at least 3 consecutive days with daily maximum temp meeting or exceeding a location-specific threshold, ranging from 25°C in north England to 28°C in London and southeast (McCarthy et al. 2019). Bottom. “Heat health alerts” heatwaves defined using regional thresholds from Public Health England for England; heatwaves in Scotland, Wales and Northern Ireland use threshold from neighbouring English region. Source: Arnell *et al.* (2021).

Few studies have modelled the impact of climate scenarios on heat related mortality and no UK or country-specific estimates have been published since the last CCRA (since the publication of Hajat *et al.* (2014)). The estimated increase in heat-related mortality has therefore not changed since CCRA2 and the figures still reflect the magnitude of the risk. Increases of approximately 260% by the 2050s and 540% by the 2080s are projected with a scenario of 4°C global warming by 2100, compared with the 2000s baseline of around 2,000 heat-related deaths across the UK assuming no adaptation occurs (Hajat *et al.*, 2014) (Figure 5.4 and Table 5.4). These estimates include population growth.



The estimates are also likely to be an underestimation of future impacts considering the higher temperatures in the UKCP18 climate projections. Projections of future temperature mortality show that heat-related mortality is likely to increase in all populations modelled, however large uncertainties about the rate of adaptation remain (Vicedo-Cabrera *et al.*, 2018). Studies for northern Europe (including the UK) indicate that climate change is likely to increase heat-related mortality significantly, with the greatest effects under the higher emissions scenarios (such as RCP8.5) (Gasparrini *et al.*, 2017; Guo *et al.*, 2018). A review of published temperature-mortality projections found that such studies generally did not report the uncertainties associated with these projections (Sanderson *et al.*, 2017).

**Table 5.4.** Mean, minimum and maximum estimates of heat-related deaths in UK regions/year/100,000 population of all ages based on an ensemble of nine climate model projections consistent with approximately 4°C global warming at the end of the century<sup>1</sup>. Source: Hajat *et al.* (2014)

	2000s			2020s			2050s			2080s		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum
North East	1.2	0.5	2.1	2.1	1.3	2.9	3.9	2.2	7.8	6.7	4.0	10.0
North West	1.3	0.3	3.1	2.0	0.8	3.9	3.7	1.8	9.0	6.2	3.0	9.8
Yorks & Hum	1.4	0.5	2.8	2.3	1.1	3.8	4.4	2.0	9.8	7.6	3.8	12.1
East Midlands	4.4	1.4	8.1	6.5	3.3	10.2	11.5	4.8	21.0	18.4	10.2	28.1
West Midlands	4.2	1.1	8.3	6.1	3.0	10.0	11.1	5.0	22.0	17.2	8.8	25.9
East Midlands	3.9	1.1	7.4	5.6	2.9	8.8	9.9	3.9	71.6	15.5	8.1	23.8
London	4.4	0.9	8.8	6.1	2.8	10.8	11.3	4.3	21.4	17.5	8.4	27.9
South East	6.3	1.5	11.4	8.6	4.6	14.1	15.3	6.7	26.1	22.9	12.8	34.1
South West	3.5	0.7	7.6	5.1	2.4	8.7	9.6	4.3	18.9	15.3	7.8	23.7
Wales	2.4	0.7	5.7	3.5	1.6	5.8	6.5	3.1	14.3	10.6	5.3	16.2
Scotland	0.7	0.2	1.5	1.3	0.3	2.2	2.4	1.3	5.2	4.4	2.6	7.2
Northern Ireland	0.9	0.3	2.3	1.6	0.6	2.6	2.9	1.5	6.1	4.9	2.9	7.2
Total UK	3.3	0.9	6.0	4.8	2.4	7.8	8.8	3.9	16.8	14.0	7.4	21.5

#### 5.2.1.2.2 Future risk – England

The UK projections of current and future mortality presented above (Hajat *et al.*, 2014) (Table 5.4) include values for all regions in England and are the main source used when considering future risks of mortality. Increases in heat-related mortality are likely to be greatest in the Southeast Region.

A comprehensive assessment of overheating risk in new build homes (Research into Overheating in Homes) has been published by MHCLG in response to the last CCRA2 and the National Adaptation Programme. Phase 1 assessed the risk of overheating of new homes in England against the new CIBSE TM592 overheating criteria (MHCLG, 2019b, 2019c). Phase 2 assessed the cost-benefit analysis of different options for space cooling. The study demonstrated that during warm years, overheating will occur in most new homes in most locations in England, particularly London. The research also showed that mitigation techniques, such as solar shading and increased ventilation, are highly effective at reducing indoor temperature, which in turn reduces the risk of mortality and the impact on productivity associated with sleep loss.

#### 5.2.1.2.3 Future risk – Northern Ireland

Climate change is projected to increase heat-related mortality in Northern Ireland (Table 5.4). Hajat *et al.* (2014) estimate that heat related deaths will increase to around 30–115 per year by 2050 and 55–135 per year by the 2080s in the scenario of 4°C global warming at the end of the century, assuming no population growth.

<sup>1</sup> UKCP09 HadRM3 perturbed-parameter ensemble with the SRES A1B scenario

A modelling study of indoor conditions in Belfast under future climates found that there was a risk of increased overheating from the 2050s, assuming no changes in occupant behaviour or retrofitting (McGrath *et al.*, 2016). It was suggested that some houses would require mechanical cooling or other housing interventions (shading) to ensure comfortable internal temperatures.

#### 5.2.1.2.4 Future risk – Scotland

Climate change is projected to increase heat-related mortality in Scotland (Table 5.4). Hajat *et al.* (2014) projections estimate that heat related deaths would increase to around 70-285 per year by 2050 and 140-390 per year by the 2080s in the scenario of 4°C global warming at the end of the century, assuming no population growth. Modelling by Arnell *et al.* (2021) indicates considerable uncertainty in the temperature projections for Scotland (see Figure 5.3) indicating that an assessment of future heatwave risks in Glasgow is likely to be an over-estimate for future risks (O'Neill and Tett, 2019).

#### 5.2.1.2.5 Future risk – Wales

Climate change is likely to increase heat-related mortality in Wales (Table 5.4, Figure 5.3). The health impacts of heat risks are discussed in the UK section. Hajat *et al.* (2014) estimate that heat related deaths will increase to around 100–450 per year by 2050 and 170–510 per year by the 2080s in the scenario of 4°C global warming by 2100, assuming no population growth.

The Welsh Government, as part of a Building Regulations review, commissioned research to extend MHCLG's overheating study to new homes in Wales (Welsh Government, 2021a). This assessment was carried out using the CIBSE TM59 methodology, using future weather files for Cardiff. The weather data adopted represented the time period 2011-2040 under a high emissions, 50<sup>th</sup> percentile climate scenario. This aimed to represent a moderately warm summer with around a 1-in-7 chance of a similar weather event occurring. The overheating risk was assessed on buildings classified as being occupied by vulnerable and fragile persons, resulting in the risk criteria being more stringent. The research showed that two dwelling types are at particular risk of overheating: flats (due to inherent limitations in removing heat gains) and homes that do not have adequate cross-ventilation to remove heat gains.

#### 5.2.1.3. Lock-in and Thresholds (H1)

There is considerable risk of lock-in for this risk because a significant part of the built environment in the UK is not adapted to future climates (CCC, 2019a). There is a potential lock-in for dwellings and other buildings that are not adapted. Most countries have targets for building new homes (a significant number in England) (see Table 5.2) and it is important that these are designed appropriately for future climates to avoid lock-in. New homes often have high levels of insulation and air tightness, low thermal mass and large glazing areas. In addition, new build flats are often high density, single-aspect with a lack of effective and/or secure ventilation.

There are lock-in risks for poor refurbishment and reuse of older or non-residential buildings that do not adequately consider overheating and the nature of the existing building fabric and building use. There are also lock-in risks for urban areas that enhance rather than reduce urban heat islands.

Heat responses are subject to a range of thresholds – both in relation to the observed relationships between mortality in specific populations and in relation to tolerable risks for indoor overheating. WHO guidance on thermal comfort states that temperatures above 24°C can cause discomfort, particularly in the more vulnerable and susceptible members of the population.

It is difficult to establish a definition of thermal comfort that applies to everyone as many environmental factors affect an individual's thermal comfort (including air temperature, radiant temperature, air speed and humidity, personal factors (such as age, gender and state of health), clothing and activity levels). For assessing the overheating risk in buildings, CIBSE have developed an adaptive methodology to assess the predicted level of thermal comfort within a building (CIBSE TM52: The Limits of Thermal Comfort: Avoiding Overheating in European Buildings). The adaptive thermal comfort model is based on the principle that an individual's thermal expectations and preferences are determined by their experience of recent (outdoor) temperatures and a range of contextual factors, such as their access to environmental controls.

The heatwave plan in England has developed regional thresholds for triggering actions; for example, Level 3 alerts are triggered when the maximum temperatures exceeds 32°C for two days in London, and approx 30°C in other regions (PHE, 2018b). These thresholds are currently under review.

#### 5.2.1.4. Cross-cutting risks and inter-dependencies (H1)

Heat risks, particularly in relation to high indoor temperatures, are important for other risks:

- Risk H6 on future demand for space cooling to manage heat risks.
- Risk H12: Risks to health and social care delivery.
- Risk H13: Risks to schools and prisons.
- Risk B6: Risks to business from reduced employee productivity due to infrastructure disruption and higher temperatures in working environments.

Heat impacts should be considered in the context of multiple hazards.

- High temperatures are likely to coincide with pollution issues, particularly ground-level ozone (see Risk H7).
- High temperatures are a factor that increase the risk wildfires and associated pollution episodes (H7) (Box 5.4).
- High temperatures and prolonged heatwaves are likely to occur with drought events and possible limitations in access to household water supplies (H10).

In terms of adaptation response (cross-chapter issues):

- Chapter 3 (Berry and Brown, 2021) discusses the potential for greenspace and other green infrastructure (nature-based solutions) to lower outdoor temperatures by moderating urban heat island effects.
- Chapter 4 (Jaroszowski, Wood and Chapman, 2021) describes the risk of high temperatures to infrastructure, including transport (roads, rails) and risk to energy supply (power outages).

The COVID-19 pandemic may have increased risks associated with high temperatures in the UK. Many individuals are more susceptible to both COVID-19 and heat stress, such as older persons and those with chronic health conditions, and persons living in residential care. Epidemiological research to understand how these risks may have affected population health has not been completed. However, the larger than expected impacts of the heatwaves in the summer of 2020 indicate that the COVID-19 pandemic may have exacerbated heat risks (PHE, 2020b).

#### 5.2.1.5. Implications of Net Zero (H1)

There is new evidence regarding the risks of overheating in low energy dwellings (e.g. Morgan *et al.*, 2017; Gupta and Gregg, 2018; Mitchell and Natarajan, 2019). The reduction of emissions from the housing sector is a key part of the government's Net Zero strategy. Policy measures that increase household energy efficiency, that both increase air-tightness and reduce ventilation, have implications for overheating risks (Mulville and Stravoravdis, 2016), poor indoor air quality and moisture-related damage unless designed appropriately. Thus, a focus on Net Zero without adequate consideration of adaptation measures can cause climate risks to increase due to energy efficiency programmes. The CCC's sixth carbon budget pathways for reducing emissions in the UK take into account the need to assess ventilation and passive cooling alongside energy efficiency measures when retrofitting existing residential buildings (CCC, 2020).

The implications for using air conditioning for achieving Net Zero are discussed in Risk H6.

#### 5.2.1.6 How will Heat Risks affect Health and Social Inequalities? (H1)

Overheating was found to occur disproportionately in households with vulnerable occupants (Vellei *et al.*, 2017). There is also good evidence that older persons and persons with pre-existing conditions are most at risk of heat-related mortality. Heat risks are very high for persons in residential care (see Risk H12). Additionally, these groups of people tend to spend more time in their homes, possibly with reduced capacity to adapt their circumstances and their environment in order to become more comfortable.

There is little evidence that heat risks are concentrated in low income households. A study of heat-related mortality in London found some evidence that heat risks were higher in low income areas but this effect was relatively small (Murage *et al.*, 2020). Any large scale increase in future reliance on mechanical cooling would potentially increase the inequality in heat risks (as currently seen in the US). Low income households may be unable to afford retrofitting measures, or installation and maintenance costs associated with space cooling measures to reduce heat exposure (Sanchez-Guevara *et al.*, 2019). Future summer household energy costs are discussed in more detail in Risk H6.

## 5.2.1.7 Magnitude scores (H1)

Heat risks are assessed as high across the UK based on the estimated heat-related mortality in each country. The estimates of heat-related mortality are robust and consistent with estimates from other countries. Heat-related mortality estimates do not provide a measure of number of life-years lost, and more evidence is needed on the social and morbidity impacts of hot weather, as well as the economic costs. In England, the impacts of heatwaves are also significant (see above) but it should be noted that most heat-related deaths occur outside recognised heatwave periods.

Modelling studies indicate that heat-related mortality is likely to increase significantly in the future under high temperatures with no additional adaptation. Estimates for future heat-related mortality in Wales, Scotland and Northern Ireland reflect both their relative smaller populations, less exposure to high temperatures, and also less sensitivity to hot weather. However, the impacts are still significant and, based on Table 3 in Chapter 2 (Watkiss and Betts, 2021), have a high magnitude. Estimates for Scotland and Northern Ireland are assessed as low confidence as there is less confidence in these estimates and very few observational studies on heat impacts. Projections of future heat-related risk are sensitive to the projections in temperature, therefore high temperature projections will entail larger heat risks.

**Table 5.5.** Magnitude score for risks to health and wellbeing from high temperatures

Country	Present Day [heat-related mortality]	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	High  (High confidence)	High  (High confidence)	High  (High confidence)	High  (High confidence)	High  (High confidence)
<b>Northern Ireland</b>	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Scotland</b>	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Wales</b>	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)

## 5.2.2 Extent to which the current adaptation will manage the risk (H1)

### 5.2.2.1 Effects of current adaptation policy and commitment on current and future risks (H1)

#### 5.2.2.1.1 UK-wide – potential adaptation responses for overheating

There are three main policy strategies for addressing heat risks in the community:

- Public health activities that encourage behavioural change for high risk groups and care-givers for vulnerable individuals, both long term preparedness and acute actions associated with heatwave alerts. Public health interventions include weather-based advisories (heat alerts), health education, and provision of cooling shelters (Bundle *et al.*, 2018).
- Designing new houses and housing developments to take account of overheating risks and increasing incentives for retrofitting existing houses.
- Planning guidance and methods for urban cooling (reducing outdoor temperatures), including nature-based solutions, and changes to building materials.

In addition, robust EPRR (emergency preparedness, response and resilience) arrangements are an adaptation measure, led by local interagency partnerships. The occurrence of major heatwave events in Europe, the US and Australia has led to significant developments in measures to reduce heat impacts in the general population, in high risk groups (see Social Care, Risk H12) and in workers (see Chapter 6: Surminski, 2021) (WHO, 2021). The evidence on the effectiveness of some heat-health interventions has also increased, particularly for heat alert systems, health education and risk communication, and Heat Health Action Plans (WHO, 2021).

Currently, there is little accessible information for the general public on how to manage overheating in buildings (Power *et al.*, 2020). There is a lack of information on how people can operate their building effectively or guidance on what they could have done to their home to reduce overheating risk.

Passive cooling measures (as opposed to mechanical) consist of reducing internal heat gains, utilising thermal mass, enhancing natural ventilation and reducing solar gain through the windows and fabric of the building. When installed and operated correctly, some low-regret passive adaptations can provide significant reductions in indoor temperatures with relatively small installation and operating costs (Mavrogianni *et al.*, 2014; Wood Plc, 2019). Adaptations to counter overheating may be applied sequentially to reduce or eliminate overheating at the lowest potential costs (which can be assessed using Marginal Abatement Cost Curves) (Li *et al.*, 2019). The efficacy of a number of heat adaptations for passive cooling has been tested for buildings to reduce overheating risks, based on modelling studies in individual dwellings:

- Improved ventilation (Taylor *et al.*, 2018a; Tink *et al.*, 2018; De Grussa *et al.*, 2019; Li *et al.*, 2019)
- External shading and shutters (Porritt *et al.*, 2012; Gupta and Gregg, 2013; Taylor *et al.*, 2018a; De Grussa *et al.*, 2019)
- Internal blinds or curtains (Tink *et al.*, 2018; Li *et al.*, 2019)



- Cool and green roofs (Virk *et al.*, 2014)
- Reflective surfaces (Taylor *et al.*, 2018b)

Loft and wall insulation can help to prevent heat penetration through roofs and walls. However, once heat has entered a home, insulation can reduce heat loss through the building fabric at night. The marginal increase in overheating risk from internal solid wall insulation were shown to be mitigated against with the use of shading using internal blinds and night ventilation (Tink *et al.*, 2018). Similarly, external shutters were able to mitigate the increase in overheating risk caused by a full retrofit of dwellings, including additional insulation and air tightening (Taylor *et al.*, 2018a).

Mechanical cooling options, such as air conditioning, may be increasingly used in the future. The implications for increased penetration of air conditioning for summer energy costs to households are discussed in detail in Risk H6.

There are some questions about the practicality of certain adaptation measures for dwellings. In the UK, many windows open outwards, meaning that external shutters may not be practical (De Grussa *et al.*, 2019). Similarly, the roof structures of the existing housing stock may not be capable of withstanding the additional weight of green roofs. Changing the reflectivity of roofs may help to reduce summertime indoor temperatures, but may do so with a wintertime space heating penalty (Taylor *et al.*, 2018a). It is also worth noting that some passive cooling measures become less effective at higher temperatures. Fans are less effective at very high temperatures although this is still subject to some debate.

Planning guidance for enhancing green space and urban cooling measures, including nature based solutions, has the potential to reduce urban heat islands and moderate outdoor temperatures. Adaptation to climate change is part of planning policy and guidance (see more detailed discussion in section 5.2.3). There has been extensive research describing and modelling urban heat islands (UHI), particularly in London and Birmingham. There is also evidence regarding the effectiveness of specific building modifications (e.g. green roofs, trees, green and blue space) on outdoor cooling. For example, a simulation study of cool roofs in the West Midlands estimated that the introduction of cool roofs reduced population-weighted temperature by 0.3 °C, and could potentially offset 25% of heat-related mortality due to the UHI during heatwaves (Macintyre and Heaviside, 2019). A study in London also found that implementing cool roofs could reduce maximum air temperature by 1 °C in summer (Macintyre and Heaviside, 2019). A review on effectiveness of greenspace interventions found that there was relatively little published information on reducing heat islands (WHO, 2017).

Green infrastructure has the potential to reduce urban temperatures. Increasing green infrastructure also has multiple benefits (these ecosystem services are described in detail in Chapter 3: Berry and Brown, 2021) and can include water quantity and quality benefits, potentially reducing negative air quality issues for human health (Risk H7), and the amenity value or broader cultural and health benefits (Risks H11 and H2) from contact to nature. However, as with risks to landscape features (Risk N18), climate change risks in combination with other pressures (e.g. from pollution) may act to degrade these benefits without further planned adaptation.

Across the UK, housing policy and planning policies that could enforce or incentivise changes to new housing designs are devolved. The current policies and evidence of effectiveness are reviewed in each country separately below and also summarised at the end of the chapter (section 5.15.3).

### 5.2.2.1.1 England

There is new evidence since CCRA2 on the effectiveness of housing interventions to address overheating. However, progress in policy change has been slow. The CCC's forthcoming 2021 progress report has found that policies to address overheating risk through building design and orientation are generally not included in Local Plans that are used to assess planning applications and it is not known the extent to which overheating is being included in recently refreshed local plans (CCC, 2021).

Overheating could be addressed in the design of new homes (and in major refurbishments) through building regulation and other statutory measures to enforce housing quality. There is provision within Part L of the Building Regulations 2010 for limiting heat gains in new dwellings, which already applies to solar gains in summer. Part L requires energy efficiency standards and puts in place rules to ensure that solar gains are not excessive and heat gains from uninsulated pipes are controlled, in order to help minimise fuel and power use (rather than to protect health or thermal comfort per se).<sup>2</sup>

In early 2021, the Ministry of Housing, Communities and Local Government (MHCLG) published the Future Buildings Standard consultation, proposing a new legal requirement as a new part of Schedule 1 of the Building Regulations (MHCLG, 2021). The functional requirement would require that the person carrying out work on new residential buildings must reduce overheating risk by limiting solar gains and removing excess heat through passive cooling measures. If brought into policy this would help tackle the risk of overheating in new buildings. However, the outcome of the consultation will only be published following the CCRA Technical Report publication.

The London Plan (GLA, 2016) encourages passive cooling in major developments by requiring developers to demonstrate "...how they will reduce the potential for overheating and reliance on air conditioning systems". A detailed CIBSE TM 52 or CIBSE TM 59 overheating assessment is required when applying for planning permission. Overheating assessments using dynamic modelling are more difficult to pass than those in the SAP (Bateson, 2016).

The above measures could compel changes to new build dwellings. However, existing buildings will require retrofitting to address overheating, alongside measures to reduce greenhouse gas emissions. There are currently no incentives to include overheating measures via retrofit. There is also little

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<sup>2</sup> To support compliance with Part L of Building Regulations, Appendix P of the Standard Assessment Procedure contains a method for assessing excessive internal heat gains. This method is based on a set of average assumptions on internal heat gains, current mean external temperature in summer, wind speed, and solar radiation. The method assumes excessive heat gains and therefore non-compliance with Part L if there is a high risk of overheating, measured as the monthly average internal temperature in summer exceeding 23.5°C. The guidance supporting Part L suggests that additional measures such as solar shading can be built into designs to take future climate change into account, but this is not controlled under Building Regulations.

evidence of changes in behaviour in response to heat, for example how occupants can operate their building effectively or guidance on how to reduce impacts of overheating (Power *et al.*, 2020). Retrofitting options that address overheating will need to be tailored to each building (type, construction), occupancy pattern, location, and orientation. Options also need to consider other concerns, including low carbon, but also cold, flooding/moisture and fire risks. The ARCC project concluded that no single solution fully addresses the overheating risk so a combination or package of adaptation options is likely to be needed to reduce the risk of overheating (ARCC, 2012).

There has been little progress in addressing outdoor heat management through planning. The National Design Guide includes multiple references to climate change and risk mitigation. Several modelling studies have quantified the changes in temperature exposure associated with aspects of building design (e.g. green space, green roof, white roof, etc.) (Mavrogianni *et al.*, 2012; 2014). The effect on indoor or outdoor temperatures are generally modest compared to housing interventions discussed above.

The Heatwave Plan for England (HWP) was first implemented in 2004 and has then been regularly updated to take account of new research. The NHS and Public Health England update the Heatwave Plan for England on a regular basis. It was most recently refreshed in 2018 (PHE, 2018b). The heat and cold alert systems/weather plans are currently (2020) being revised into a single year-round plan. The Department of Health and Social Care (DHSC) commissioned an independent evaluation of the implementation and potential effects of the HWP in 2019 (Williams *et al.*, 2019). The evaluation looked at both mortality outcomes and interviewed health staff about implementation. The key findings confirmed that hot weather does cause an increase in deaths and hospital admissions. However, heat-related death rates had been generally falling before the Heatwave Plan was introduced, and were continuing to go down (the most recent heatwaves were not included in the analysis and no updated estimates are available). There was insufficient evidence that the Heatwave Plan itself made a difference to this. Evidence did suggest that the Heatwave Plan was good at protecting people during the alert periods (the hottest days), but less effective in hot weather where no alert was issued. It also highlighted that people were not always taking heed of the advice about hot weather. Overall, the general public felt positive about warm summer days and most did not feel that hot weather was a risk to their health, including people over the age of 75. As a consequence, many people, including the most vulnerable, were not taking all of the Heatwave Plan's recommended actions to protect themselves and others.

The second National Adaptation Programme (NAP2) highlighted actions to increase green infrastructure in urban areas, implement green infrastructure standards, undertake research in overheating in homes and further develop the Heatwave Plan.

#### 5.2.2.1.2 Northern Ireland

Northern Ireland does not currently have a heatwave plan.

The Department of Communities is developing a new Housing Strategy that will set out targets for new homes. The NI Strategic Planning Policy Statement states that "the planning system should help to mitigate and adapt to climate change". However, there is little evidence regarding specific actions

for managing heat risks (indoor or outdoor). Belfast City Council and many other bodies are exploring how to deliver an urgent and ambitious housing retrofit programme which is driven by Net Zero carbon targets. The focus on Net Zero could easily cause climate risk to be missed within such a programme unless they are included explicitly.

Northern Ireland has its own Building Regulations, the most recent of which were published in 2012. Part F relates to limiting internal thermal gains and Part K to adequate ventilation but currently there is no building standard to specifically address overheating. The NI building regulations are currently under review by the Northern Ireland Building Regulations Advisory Committee convened by the Department for Finance. Retrofitting is also being supported by activities at the city level (e.g. Belfast City Council).

#### 5.2.2.1.3 Scotland

Public Health Scotland does not currently have a heatwave plan. However, Scotland is part of the extreme weather system that now includes heatwaves. The second Scottish Climate Change Adaptation Programme (Scottish Government, 2019a) recognises the risks to homes in Scotland from overheating, and that the building stock will need to adapt to future changes in the climate. It has specific actions to continue support for urban greening through the Green Infrastructure Fund and Green Infrastructure Community Engagement Fund.

The Building (Scotland) Act 2003 mandated Building Regulations that are specific to Scotland. The Building Standards System sets out the essential standards to be met when building work or a conversion takes place. The application of these standards is verified at building design stage and on completion by Scottish local authorities who are appointed as ‘verifiers’ of the building standards system. Responsibility for compliance with regulations rests with the ‘relevant person’, commonly the building owner or developer. The CCC’s progress report to the Scottish Government reported that there are up to date Building Standards in place for flood resilience, moisture penetration from heavy rain, heating and ventilation, but there is no strategy for retrofitting existing buildings with adaptation measures and only limited guidance is available on overheating in buildings (CCC, 2019c).

As part of the UK decarbonisation strategy, a review of energy standards is underway. This review will include further consideration of how standards may increase or decrease overheating risks in new buildings in the future and considering climate change. The next set of standards and supporting guidance will be introduced in late 2021.

National Planning Framework 3 does make reference to the role of green infrastructure in enhancing climate resilience, although not heat islands specifically.

#### 5.2.2.1.4 Wales

Welsh Government’s second adaptation plan, Prosperity for All: A Climate Conscious Wales (2019) includes an action to ‘increase understanding of the risk increased temperatures bring to public health and well-being’ (Welsh Government, 2019f). The adaptation plan sets out Public Health

Wales' (PHW) intentions to improve knowledge and use of trend data to increase understanding of the risk and improve collaboration to ensure effective sharing of this information.

PHW has a strategy for extreme weather events, and it provides public health guidance to the general public in hot weather and for those caring for children. The public health advice is available for different target groups and is available year-round on the PHW website. A commitment has been made in *Prosperity for All: A Climate Conscious Wales* for PHW to revise this advice. Interviews with stakeholders revealed a need not just to plan for winter, but to take an approach of continuous preventative planning and long-term planning for increasing incidence of extreme weather events caused by climate change (Azam *et al.*, 2019). Public Health Wales is in the process of undertaking a health impact assessment of climate change but this is delayed due to the COVID-19 pandemic. Area Statements published by Natural Resources Wales look to urban green infrastructure as a means to reduce outdoor temperatures in urban areas (NRW, 2020a).

Building regulations for Wales do not currently address overheating risks. The Welsh government ran two consultations in 2020 on Building Regulations. The first on changes to Part L (conservation of fuel and power) and Part F (ventilation) of the Building Regulations for new dwellings. The second consultation covered Part L and F proposals for existing dwellings and proposals to mitigate overheating in new dwellings (Welsh Government, 2021a). At the time of writing (April 2021), the consultation had closed and the Welsh Government were reviewing responses. The consultation proposed that a new part of the Building Regulations (Part S) is introduced which is focussed on overheating risk. If brought into policy, this would require dwellings to be designed and constructed in a way to reduce summertime overheating and ensure mitigation measures are safe, secure and reasonably practical for occupants. Developers would also be required to provide information to occupants about the dwelling's overheating strategy.

The Welsh Government also commissioned research on heat effects on employee productivity (see Risk B5, Chapter 6: Surminski, 2021) to inform guidance from Business Wales on how to adapt to increasing temperatures and keep employees safe. *Prosperity for All: A Climate Conscious Wales* states the Welsh Government is working with PHW to develop extreme weather guidance under the *Llwybr Newydd: Wales Transport Strategy 2021* (Welsh Government, 2021b), and that contracts for new rolling stock will also consider overheating on trains.

#### 5.2.2.2. Adaptation shortfall (H1)

In our view, the shortfall in housing policy to address overheating that was identified in the CCRA2 Evidence Report remain. These gaps have been highlighted by the Environmental Audit Committee (2018a). At the time of writing there are currently no policy levers to address the health effects of overheating through passive cooling or other means in new homes and no incentives to address overheating in existing homes through retrofitting adaptation measures.

There is some evidence of work underway in England and Wales to develop policy further to address overheating through amendments to Building Regulations, but at the time of writing this has not yet come to completion and been introduced into policy.

Further, there is evidence that new homes may be at greater risk of overheating due to changes in energy efficiency regulations that are part of the interventions needed to achieve Net Zero, if appropriate ventilation and adaptation measures are not considered at the same time.

England has a Heatwave Plan that has been evaluated to be somewhat effective in relation to heat warnings. The devolved administrations do not currently have specific heatwave plans, though they do have severe weather alert systems and information about what actions to take during a heatwave.

There is very little evidence that the risks from increasing extreme heat in urban heat islands are being addressed through planning and nature based solutions, although there is good evidence that some specific interventions are effective with regard to localised shading and cooling effects, and have significant co-benefits (see Chapter 3: Berry and Brown, 2021). There are various actions underway to increase and improve urban greenspace across the UK, but as yet a lack of evidence to show that the proportion of urban areas made up of greenspace is increasing.

There remains uncertainty regarding the need for near-term heat adaptation plans in Scotland and Northern Ireland and this will be depend on future rates of warming.

### 5.2.2.3 Adaptation Scores (H1)

The adaptation scores are assessed on the two key aspects of policy and practice: building standards that address overheating and having a national heat health action plan. Although building regulations and standards are in the process of being revised, these have not yet been updated into policy in any country. England and Wales have public health strategies in place (England has the Heatwave Plan for England) and therefore have been assessed as partially managing future risks.

<b>Table 5.6. Adaptation scores for risks to health and wellbeing from high temperatures</b>			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially	No	No	Partially
(High confidence)	(Medium confidence)	(Medium confidence)	(Medium confidence)

### 5.2.3 Benefits of further adaptation action in the next five years (H1)

#### 5.2.3.1 Additional planned adaptation that would address the adaptation shortfall (H1)

There are benefits of adaptation in the next five years, particularly to avoid lock with housing and urban designs that are not adapted to future temperature extremes.

The requirements for housing to be suitable for future climates require coordinated action and optimisation of outcomes against the range of objectives (climate and non-climate related). The evidence indicates that currently decarbonisation (Net Zero) and adaptation policies and strategies are not well aligned (CCC, 2019d). The EAC (Environmental Audit Committee, 2018a) highlighted the

need for cross-departmental policy and it is important that overheating risks are addressed in all types of buildings where people spend significant time.

The CCC have made a number of recommendations to Government in relation to housing across the UK (CCC, 2019a):

- A legal standard or regulation should be introduced to address overheating risk for current and future climates at design stage of new-build homes or renovations.
- Ensure that passive cooling measures are prioritised over mechanical cooling where a risk of overheating is identified.
- Further action is needed to better understand when overheating occurs in existing homes in order for passive cooling measures and behaviour change programmes to be targeted effectively.

Climate change presents several risks for housing alongside overheating, such as flooding and damp risks. It is likely to be more effective and less expensive (especially for social housing landlords) to address these risks at the same time through retrofitting to address overheating. In our view, there is a need for increased guidance and incentives to address overheating in existing homes through retrofitting, given the lack of information available on what measures are effective for householders (CCC, 2019a; Power *et al.*, 2020).

Based on the assessment above, our view is that continuous preventative planning to include long term risks would have benefits in the next five years, including consideration of longer term risks within current emergency preparedness planning.

Air conditioning (or mechanical space cooling) has additional benefits and potential harms, in addition to the increased household energy costs (see Risk H6 for a more detailed discussion). There may also be other health dis-benefits from air conditioning; there is some evidence regarding the negative effects of using air conditioning, including the understanding that it can limit acclimatisation (Yu *et al.*, 2012). The presence of air conditioning in housing is currently low in the UK (at about 3% of homes) (Khare *et al.*, 2015). Although uptake may increase autonomously in the future, relying on air conditioning to deal with the risk is a potentially maladaptive solution, and it expels waste heat into the environment – thereby enhancing the urban heat island effect.

#### 5.2.3.2 Indicative costs and benefits of additional adaptation (H1)

The quantified benefits and costs of addressing overheating in buildings involves a range of assumptions about mortality risks associated with overheating.

Several studies have compared the costs of mechanical vs. passive methods of space cooling in new houses and retrofits (Grant *et al.*, 2011; Frontier Economics, Irbaris LLP and Ecofys, 2013; Adaptation Sub-Committee, 2014; Li *et al.*, 2019; Wood Plc, 2019). These generally report positive benefit to cost ratios or high cost-effectiveness (£ / % reduction in temperature). This indicates the potential for low regret options but also that there is a need (and opportunity) to address further risks in climate smart design to address lock-in risks and co-benefits.

This is a complex area to assess costs (to households) given the multiple co-benefits and potential harms for each housing intervention. No-cost options to manage overheating can be effective to some extent, such as utilising increased natural ventilation (opening windows), using existing blinds and curtains during the day to limit heat gain and changing behaviours. Shading is the most cost-effective option for cooling houses (Wood Plc, 2019). Many low-carbon retrofit options share commonalities with adaptation options and so could potentially share the cost and reduce overall costs.

There is also analysis of the benefits and costs of heatwave warning systems. Several studies report high benefit to cost ratios for future heat related mortality (Bouwer *et al.*, 2018; Chiabai *et al.*, 2018) including analysis in the UK for the Heat Health Watch System (HHWS) (Hunt *et al.*, 2017). Benefit to cost ratios are high and increase significantly under climate change.

The studies assume that the cost of operating the warning system increases under future climate change, but this may not be the case as the health system response may become more efficient, and the costs to the provider (e.g. the Met Office) are assumed to be fixed. As discussed above, the heat alert systems alone do not fully manage the health risk in the population (Watkiss *et al.*, 2019b).

#### 5.2.3.3 Urgency Scores (H1)

This assessment of current evidence indicates that risks to health and wellbeing from heat may be higher than previously understood (in CCRA2). In addition, there has been little progress in addressing these risks through changes to building policy across the UK, and an adaptation shortfall is present in all UK countries. For both these reasons, this risk has been scored as more action needed for each UK country. Confidence in the score is high in England and Wales due to more evidence regarding heat impacts on health and also the higher absolute exposures to high temperatures now and in the future.

<b>Table 5.7. Urgency scores for Risks to health and wellbeing from high temperatures</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	High	Low	Low	High

#### 5.2.4 Looking ahead (H1)

Key uncertainties remain regarding the health burden and avoidable burden from high temperatures, and there is a need to understand non-fatal and long term impacts on health and wellbeing.

Projections of future impacts do not adequately consider adaptation either through behaviour change (acclimatisation) or changes to the built environment. Several key measures for overheating (e.g. fans)



are not effective at very high temperatures and these also need to be considered in more detail in conjunction with the likelihood of higher rates of warming (Taylor *et al.*, 2018a; 2018b).

Adaptive management approaches in the built environment have received less attention in the UK with respect to heat risks. There may be benefits from greater investment in early planning to start preparing for long-term heat risks, particularly as there are potentially large future risks and the large differences in potential action that might be needed across different pathways (eg. for pathway to 2°C or 4°C global warming by the end of the century). Examples of pathway approach (RAMSES, 2017) include planning in London (Kingsborough *et al.*, 2017) but this does not address integrated policy across the health, buildings and land-use domains.

## 5.3 Opportunities for health and wellbeing from warmer summers and winters (H2)

The physical and mental health benefits of increased physical activity and contact with nature are well established, but there is limited evidence on the extent to which a warmer climate will increase these activities. There are no current policies in the public sector to increase these opportunities, but the case for government intervention specifically as a climate change adaptation response is also uncertain. The burden of ill-health from cold and cold homes remains significant in the UK and is a priority for public health and local government action. Modelled estimates show that climate change is likely to reduce the burden of cold related mortality, however, the overall burden remains high, even to the end of the century. Population aging is likely to offset some of the benefits from warmer winters for cold-related mortality.

### 5.3.1 Current and future level of opportunity (H2)

Note: It has not been possible to split the evidence by UK country for this opportunity. The evidence regarding health benefits applies to all countries.

#### 5.3.1.1 Current and future opportunity – UK wide (H2)

There are benefits and opportunities associated with higher temperatures. Climate change is increasingly recognised as a factor that may influence the recreational use of outdoor space and the natural environment. Chapter 1 (Slingo, 2021) reports an overall warming trend in the UK, including a reduction in cold days and extreme winters. Extreme cold daily temperatures still occur, such as in March 2018, but have become less frequent (Stott and Christidis, 2020). Climate change may affect the risk of future winter storms.

Estimates of future cold-related mortality under climate change indicate that there will be a reduction in cold related mortality. Approximate 3% of total mortality per year is attributable to cold (Low temperatures) (Arbuthnott *et al.*, 2020). There have been few published estimates of reductions in cold under climate scenarios specifically for the UK but estimates for northern Europe

(Gasparrini *et al.*, 2017) show significant reductions when temperature alone is considered. Winter excess mortality is a reflection of both cold exposures and also seasonal infections, along with other factors, and is therefore a poor indicator of the burden associated with cold (Hajat *et al.*, 2016). Reductions on cold are discussed in Risk H6 on energy costs. Damp homes are discussed in Risk H5 on building fabric – it is likely that the increase in heavy rainfall may offset any benefits of temperature increases in terms of moisture damage to dwellings – but these effects may vary regionally. A minor benefit associated with milder winters is potential reduction in the risk of mould growth, provided there is sufficient ventilation to remove moisture from the indoor air.

UK summer temperatures are expected to rise with a longer summer season. Possible outcomes of this may be an increase in use of outdoor space for both physical activity, leisure activities, cultural activities, and domestic tourism (Elliott *et al.*, 2019). A key positive impact of population health would be an increase in physical activity, particularly in individuals who have limited access to formal exercise spaces such as gyms and leisure centres due to cost or mobility constraints (Elliott *et al.*, 2019). The evidence for improvements in mental health through use of green and blue space is robust (Braubach *et al.*, 2017). It should be noted that warmer, wetter summers will limit the future benefits and opportunities (see Chapter 1: Slingo, 2021).

Increased time outdoors may increase Vitamin D exposure which is important for bone health and the immune system (SACN, 2016). The primary source is through exposure to sunlight, thus an increase in use of outdoor space may lead to an increase in Vitamin D concentrations and incur positive physical health benefits (SACN, 2016). There is currently some debate about recommendations for Vitamin D exposures and supplementation (including the fortification of flour). Advice regarding increased sun exposure are still being formulated given the ultraviolet radiation (UVR) has health risks (cancer, immunosuppression and sunburn).

A further opportunity of climate change is the benefits for agriculture and implications for nutrition (see Chapter 3: Berry and Brown, 2021) (Food Standards Agency, 2015). Northerly soils typically produce wheat that is higher in selenium concentrations. The UK population on average fall below the recommended daily intake of selenium (Low intake is linked to some cancers, cardiovascular disease, cognitive decline and thyroid disease (Food Standards Agency, 2015)). The introduction of new crops such as soya, lupins, borage and evening primrose may also have potential to improve nutrition (Office of Science and Technology, 2019).

#### 5.3.1.2 Lock-in and thresholds (H2)

It is not clear what the risk of lock-in are for this opportunity. The potential interventions are largely focussed on changing people's behaviour. However, there are some issues that relate to designing the built environment that encourage physical activity and contact with nature.

There is no evidence for clear thresholds in relation to the opportunities from warmer winters. Thresholds for cold-related mortality are not well defined.

#### 5.3.1.4 Cross-cutting risks and inter-dependencies (H2)

This risk overlaps with other risks on heat (H1) in relation to the development of urban greenspace and co-benefit to health and the environment. The management of risks from cold (and cold homes) is discussed in detail in the risks on household energy use and future winter heating demand (H6).

#### 5.3.1.5 Implications of Net Zero (H2)

Reductions in cold homes can be achieved through household energy measures which are a key part of the Net Zero strategy. These issues are discussed in more detail in H6 on winter heating demand and energy efficiency.

Net Zero policies for reducing greenhouse gas emissions such as tree planting and active transport (e.g. walking and cycling corridors) could also provide opportunities for increased green space.

#### 5.3.1.6 Inequalities (H2)

There is an increasing evidence base about the differences between groups about accessing outdoor space (disability; access and perception of access). A review of access to greenspace by Public Health England (PHE, 2020d) found that people from ethnic minorities and lower income households access greenspace less and live in less green neighbourhoods compared to wealthier groups or those with a higher percentage white population.

#### 5.3.1.7 Magnitude scores (H2)

The magnitude score for this risk (Table 5.8) only applies to the opportunity from warmer summers and winters, and relates to health benefits. Scores are based purely on expert judgement given the lack of evidence.

Note that the opportunity from reductions in home heating costs are assessed separately in RiskH6 on household energy.

The benefits of less cold-related mortality are not scored in this table but it should be noted that the magnitude of the benefit is medium to high in all UK countries. Hajat *et al.* (2014) estimated current cold-related mortality as approx 41,000 deaths per year for the UK and this declines by 2% by 2050 with climate warming. Cold extremes and winter storms will still occur in the future although their frequency is expected to decline (Chapter 1: Slingo, 2021; Box 5.2).

**Table 5.8.** Magnitude score for opportunities for health and wellbeing from warmer summers and winters

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Low	Low	Low	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Northern Ireland	Low	Low	Low	Low	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Scotland	Low	Low	Low	Low	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Wales	Low	Low	Low	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

**Box 5.2. Increased risks from cold?**

There are some concerns that if cold events (such as the “Beast from the East” in 2018) are going to become less frequent in the future, it is possible that planning for cold risks will become deprioritised as a risk. The management of cold events requires investment and resources (for example, training, exercising and equipment procurement). Any decrease from current levels may therefore increase vulnerability to such future events.

It is important that activities to prevent cold deaths are maintained or strengthened. The burden of ill-health from cold, and cold homes, remains significant in the UK. Issues relating to cold remain a high priority with public health and for local government. Further, there has been concern from Local Authorities and public health agencies that the increased emphasis on managing heat risks might detract from actions to address impacts from cold.

Climate projections indicate a decline in very cold days (and other cold metrics) even at 1.5°C warming [see Chapter 1: Slingo, 2020: Figure 1.6.]. There is currently no evidence that changes in the Jet Stream will affect the frequency of cold events in the future (see section 1.8.2.)

### 5.3.2 Extent to which current adaptation will manage the opportunity (H2)

#### 5.3.2.1 Effects of current adaptation policy and commitments on current and future risks (H2)

Note: This section does not address policies to reduce cold-related deaths. Cold homes are a major determinant of cold-related mortality and morbidity (NICE, 2016). The potential benefits in terms of

indoor temperatures are discussed in detail in Risk H6 on winter and summer household energy demand. The UK countries have public health strategies to reduce excess winter mortality, e.g. the Cold Weather Plan in England (PHE, 2018a) and the Public Health Wales (PHW) strategy for winter health and well-being (Azam *et al.*, 2019). It is important the actions to prevent cold related mortality and morbidity are maintained (see Box 5.2).

#### 5.3.2.1.1 UK-wide

The benefits of increased outdoor activity are many – the key mechanisms are thought to be:

- Increased active travel (walking and cycling) reduces the risk of non-communicable diseases and improves mental health.
- Increased physical activity from increasing or improving greenspace. A review by NICE on the environment and strategies to increase physical activity (NICE, 2018) found evidence that interventions in parks and the built environment have the potential to improve health.
- Increased mental health from contact with nature (PHE, 2020d).

There have been several studies that looked at the effect of weather (temperature and rainfall) on active travel in adults and children. Overall, rainfall and snow tend to reduce physical activity (walking and cycling) in adults and children, but temperature may have a small positive effect (Chan and Ryan, 2009). A cross sectional analysis of 28 European countries found that a 1°C increase in annual mean temperature was associated with -0.94 (fewer) minutes of vigorous-intensity activity per week (95% CI: -1.66 to -0.23) but it should be noted that this effect could be driven by the very high temperature exposures experienced in southern European countries (Laverly *et al.*, 2018).

There is some scope for policy intervention to capitalise on the opportunities of warmer winters and hotter summers to encourage physical activity. There is a growing evidence base regarding interventions to increase physical activity through changes to the built environment which include increasing green infrastructure (NICE, 2018). It has been argued that a broader approach which recognises the role of supportive environments that can make healthy choices easier is required, and that both changes to the built environment and changes to behaviour are required (WHO Euro, 2017).

It can also be argued that whilst use of outdoor spaces has positive health benefits, there are also some disbenefits or risks to health. Other risks associated with more common use of the outdoors and green spaces is possible, e.g. increased contact with ticks and biting insects, higher rates of alcohol consumption from more social gatherings outdoors, and possible implications for skin cancer risk due to sun exposure and sunburn (Bruine de Bruin *et al.*, 2016; Howarth *et al.*, 2019).

#### 5.3.2.1.2 England

The 25 Year Environment Plan for England has a commitment to help people improve their health and wellbeing by using green spaces including through mental health services.

The National Planning Policy Framework sets out that planning policies and decisions should aim to achieve healthy, inclusive and safe places which enable and support healthy lifestyles, especially where this would address identified local health and well-being needs, for example through the provision of safe and accessible green infrastructure, sports facilities, local shops, access to healthier food, allotments, and layouts that encourage walking and cycling.

The Environment Bill, if enacted as is currently drafted at the time of writing will require developers to deliver at least a 10% improvement in biodiversity value (Biodiversity Net Gain). This could be through measures such as an on-site nature reserve adjacent to a new housing development which could provide an opportunity to increase green space for occupants.

Public Health England has recently published a report on improving access to greenspace (PHE, 2020d). PHE argues that local authorities can address several local issues through improving access to greenspace, including improving health and wellbeing, managing health and social care costs, reducing health inequalities, improving social cohesion and taking positive action to address climate change. There are many initiatives at the local level, including the London Plan and the Birmingham Green Living Spaces plan, that are not possible to review in detail here.

The second National Adaptation Programme's (Defra, 2018c) actions related to improving green infrastructure relate to this opportunity as well as Risk B1. Currently however, there are no specific strategies (national or local) that use climate information to optimise current plans regarding physical activity or accessing greenspace.

#### 5.3.2.1.3 Northern Ireland

The second Northern Ireland Climate Change Adaptation Programme (Daera, 2019) includes an acknowledgement of the potential health opportunities from warmer temperatures, though the actions listed are focussed on reducing fuel poverty (see risk H6). Daera is currently developing Northern Ireland's first overarching Environment Strategy with a view to seeking Executive endorsement at the time of writing. The Strategy will form part of the multi-decade 'Green Growth Framework' and is intended that the Strategy will be adopted as NI's first Environmental Improvement Plan (EIP) under the UK Environment Bill. The Environment Strategy/EIP will include short, medium- and long-term targets to improve the natural environment including health and wellbeing.

#### 5.3.2.1.4 Scotland

The second Scottish Climate Change Adaptation Programme (Scottish Government, 2019a) includes references to the health benefits from warmer temperatures and lists actions related to the Physical Activity Delivery Plan, the Natural Health Service Programme and the Walking and Cycling network as policy levers to encourage more outdoor recreation. SCCAP2 contains somewhat more information for this opportunity compared to the other UK adaptation programmes.

The Scottish Government also has several policies on greenspace and healthy neighbourhoods. Green infrastructure and active travel feature strongly in Scottish Planning Policy and National

Planning Framework 3. The Green Exercise Partnership (NatureScot, Scottish Forestry, NHS National Services Scotland, and Public Health Scotland) coordinates the NHS Greenspace Demonstration Project that promotes access to greenspace in NHS assets.

### 5.3.2.1.5 Wales

Prosperity for All; A Climate Conscious Wales (Welsh Government, 2019f) includes an acknowledgement of the potential health opportunities from warmer temperatures, though the actions listed are focussed on reducing fuel poverty (see risk H5). Public Health Wales has developed a resource to improve access to greenspace and improve health through the built environment: Creating healthier places and spaces for our present and future generations (PHW, 2018). However, it doesn't specifically address the implications of future climates.

### 5.3.2.2 Adaptation shortfall (H2)

It is not clear what additional policies may be needed to fully realise the benefits from warmer summers and winters to health and wellbeing across the UK. Some policies that are linked to this opportunity exist, but it is not clear how much additional government intervention may be needed in the future.

This assessment relates specifically to policies that look at the health opportunities of warmer weather and not for the health benefits of greenspace in general (for which there are an increasing number of activities).

### 5.3.2.3 Adaptation Scores (H2)

The current state of adaptation opportunity is assessed on the potential for government to intervene to improve health and wellbeing. In our view, the adaptation is being partially addressed in all countries because the opportunity will not be fully realised in absence of government intervention and only some elements of the enabling environment are in place. The progress on increasing contact with nature (in terms of government policies in targets) is considered part of the enabling environment for this opportunity.

**Table 5.9.** Adaptation scores for opportunities for health and wellbeing from warmer summers and winters

Are the opportunities going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially	Partially	Partially	Partially
(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

### 5.3.3 Benefits of further adaptation action in the next five years (H2)

There are clearly benefits from further investment in strategies to increase physical activity and mental health – and the opportunities for outdoor recreation and active travel.

There is little information on the costs and benefits involved in additional interventions to help address opportunities for health and well-being, but there is likely to be the potential for low-regret and low-cost interventions to help raise awareness and ensure opportunities are fully realised. There are well established interventions for public health communication and awareness raising although these have largely been targeted at impacts rather than opportunities in the health and adaptation domain to date. Interventions to enhance opportunities could lead to large economic benefits (Hunt *et al.*, 2017) in terms of societal welfare from three components: (i) lower resource costs, i.e. avoided medical treatment costs; (ii) increased opportunity costs from gains in productivity; and (iii) the avoided dis-utility, i.e. pain or suffering, concern and inconvenience to family and others. A no-regret option would be to investigate these potential benefits and look at the possible interventions to help deliver these.

#### 5.3.3.3 Urgency scores (H2)

The urgency score for each UK nation for this opportunity is further investigation because there is some uncertainty about the potential benefits that can be achieved through policy intervention – but the potential benefits are very large. Although there is insufficient policy action to address obesity, lack of physical activity and poor mental health in the UK, that is not the focus of this opportunity which relates to additional actions in response to climate change only.

<b>Table 5.10. Urgency scores for opportunities for health and wellbeing from warmer summers and winters</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	Further investigation	Further investigation	Further investigation	Further investigation
<b>Confidence</b>	Low	Low	Low	Low

### 5.3.4 Looking ahead (H2)

More research is needed on understanding behaviour for engagement with nature and how to increase physical activity (NICE, 2018). There are also evidence gaps regarding the multi-benefits of greenspace interventions (type and quality of greenspace). Research is needed to better understand how, when and where natural environments could be best used to improve health outcomes, and what the role of government should be, if any, in encouraging the public to take the opportunities of warmer conditions for increased outdoor activity.



## 5.4 Risks to people, communities and buildings from flooding (H3)

The risk of flooding to people, communities and buildings is one of the most severe risks from climate hazards for the UK population – both now and in the future. The magnitude of the current risk may have increased since the last assessment report although this not certain. Most of the present and future flood risk is in England, given its larger population. When risks are normalised by the flood exposed population (that is, the average Expected Annual Damage (EAD) per individual), people and communities in Northern Ireland, Scotland and Wales are, on average, exposed to a higher EAD than those living in England.

This risk encompasses flooding from all sources – from rivers (fluvial), the sea (coastal), surface water (pluvial) and groundwater. Risk H4 contains related information on sea level rise induced catastrophic coastal flooding or erosion of a scale that threatens the viability of coastal communities. Flooding from rivers is the dominant source in terms of potential damage but surface water flood risk accounts for a greater number of properties at risk. Coastal flooding is the most dangerous in terms of impacts for life and property but accounts for a lower number of properties at risk than those affected by surface water or river flooding. Groundwater risk dominates flood risk in some areas but has a limited contribution to the scale of national risk.

Considerable advances have been made regarding the strategic management of flood risk at national and local levels since the last CCRA, including the promotion of a cultural shift from protection to resilience, and whilst flood events have occurred, a larger number of properties have been protected than affected. Conventional flood defences (requiring both capital and revenue investment) remain the most important management approach whilst Natural Flood Management (NFM) and Property-level Flood Resilience (PFR) also contribute significantly to reducing flood related damages. Flood forecasting and warning provide an underpinning response across all portfolios. Effective spatial planning remains the only measure that can avoid flood exposure due to development. The residual risk managed by insurance reduces with a more ambitious adaptation portfolio (Enhanced Whole System) reflecting the reduction in risk achieved by other measures (Sayers *et al.*, 2020a).

Coastal risk is the most serious source of flooding, in terms of potential threat to life, due to the depths and velocity of flooding. From the analysis in the CCRA3 future flood risk report (Sayers *et al.*, 2020a), coastal flood risk is likely to continue to result in increased EAD in a scenario of global warming reaching 4°C in 2100 with high UK population growth, even with the Enhanced Whole System approach to adaptation. The analysis suggests an increase in direct EAD to residential property from £82 million today to £247 million by the 2080s. As detailed further under Risk H4, long term integrated development planning is needed to manage the current and future coastal risk to coastal communities. Coastal flood risk is a particular threat to England and Wales.

Surface water flood risk is also projected to increase rapidly with residential (direct) EAD increasing from £139 million today to £312 million by the 2080s under a scenario of 4°C global warming in 2100 with high population growth and Enhanced Whole System adaptation. Continued promotion of Sustainable Drainage Systems (SuDS) and introducing stronger requirements in England, Northern Ireland and Scotland is needed to manage the increasing risk of flooding from surface water.

The risk magnitude remains high now and in the future for all parts of the UK with more action needed due to the scale of the risk. Key areas of challenge relate to the resilience of development in flood risk areas, the limited mandatory management of surface water flooding via SuDS, the low take up of PFR and associated concerns regarding the perception of flood risk by households, and the need to implement an effective and integrated approach supporting a shift from protection to resilience.

### 5.4.1 Current and future level of risk (H3)

#### 5.4.1.1 Current risk (H3)

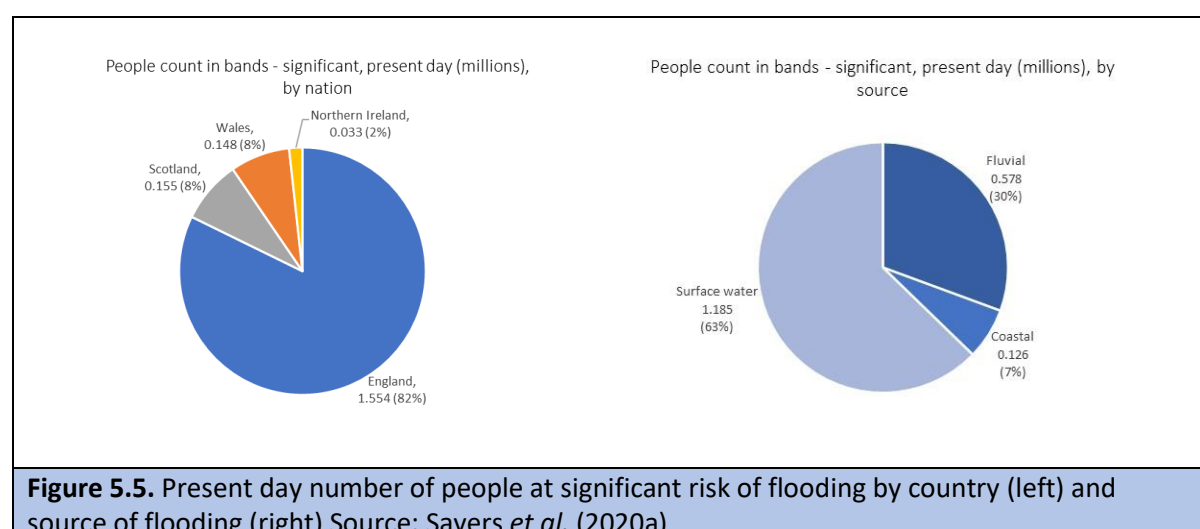
##### 5.4.1.1.1 Current risk – UK wide

The risk to people and communities from increased flood risk due to climate change is significant. It was ranked as a high risk that required further action in CCRA2 with approximately 1.4 million people across the UK at risk of frequent flooding (Sayers *et al.*, 2017a). There are now known to be just under 1.9 million people, across all areas of the UK, exposed to frequent flooding from either fluvial, coastal or surface water flooding (at a 1 in 75-year risk (1.3% Annual Exceedance Probability (AEP)) or greater) (Table 5.11). Approximately 82% of those at risk are in England, 8% in Wales, 8% in Scotland and 2% in Northern Ireland (Sayers *et al.*, 2020a). It should be noted that the increase of 0.5 million people at risk of flooding since CCRA2 (2017) does not necessarily show evidence of increased risk, as there have been a number of changes to the assessment methodology.

However, recent research has identified that climate change is causing more frequent and intense flooding in northern parts of Europe, suggesting that this increased level of risk might, in part, be attributed to climate change (Tabari, 2020).

The Future Flood Projections research commissioned to support the CCRA identifies that surface water is the dominant source of risk in terms of people affected (Figure 5.5; Sayers *et al.*, 2020a). However, when considering EAD for residential properties (direct), fluvial is the dominant source as shown in Table 5.11.

<b>Table 5.11. Present day number of people at significant risk of flooding Source: Sayers, <i>et al.</i>, 2020c</b>				
	<b>Fluvial</b>	<b>Coastal</b>	<b>Surface Water</b>	<b>All Sources</b>
<b>England</b>	476,000	102,000	976,000	1,554,000
<b>Scotland</b>	46,000	13,000	95,000	155,000
<b>Wales</b>	46,000	10,000	91,000	148,000
<b>Northern Ireland</b>	10,000	1,000	22,000	33,000
<b>UK Total</b>	578,000	126,000	1,185,000	1,889,000



**Figure 5.5.** Present day number of people at significant risk of flooding by country (left) and source of flooding (right) Source: Sayers *et al.* (2020a)

**Table 5.12.** Present day expected annual damage: residential (direct) (£m) Source: Sayers *et al.* (2020a)

	Fluvial	Coastal	Surface Water	All Sources
England	172.0	59.5	59.8	291.3
Scotland	44.3	6.4	17.8	68.5
Wales	31.6	16.0	46.9	94.5
Northern Ireland	6.9	0.2	14.1	21.2
UK Total	254.8	82.0	138.7	475.5

EAD is the expense that would occur in any given year if monetary damages from all flood probabilities and magnitudes are spread out equally over time. It is not expected that each year will provide the same damages, some years will be much higher and some lower, this is the average. Direct damages relate to property damage whilst indirect damages cover losses associated with emergency services and provision of temporary accommodation, risk to life and physical injury and impacts on infrastructure, transport, schools and leisure. Indirect damage also includes the intangible damages associated with mental health impacts assessed through a proxy of the additional costs associated with treatment and the economic impact of people being unable to work. Indirect costs are estimated at 90% of the value of direct damages in the Future Flood projections.

Since CCRA2 (2017), there have been significant advances in the development of evidence, the refinement of policy and the delivery of adaptation actions with respect to flood risk. There have also been further flood events.

Flooding is a threat to life as well as to health and wellbeing, the economy and the environment. The main risks to people, communities and buildings from flooding are:

- Death or injury from flood events.
- Long term and severe impacts on mental health and wellbeing from flooding, displacement, and being affected by flooding.
- Damage to property:
  - Structural damage and the costs of rebuilding and repair.
  - Upheaval and financial implications of cleaning up.

- Further upheaval and financial implications if residents have to move out.
- Loss of and damage to possessions.
- Disrupted access to employment, education, health services and wider facilities (see also Risk H12 in this chapter).
- Illness from biological and/or chemical contaminants arising from floods (PHE, 2014, Box 5.5).
- Loss of recreational and leisure amenity and cultural heritage (covered in Chapter 3 (Berry and Brown, 2021) and Risk H11 in this chapter respectively).

Deaths may occur from drowning and physical injury. Mortality attributable to flooding can also include car accidents and falling into fast flowing water, hypothermia, and injuries or death associated with cleaning up (including carbon monoxide poisoning). The total annual impact is uncertain as data on UK deaths resulting from flooding are not routinely reported in health or vital registration data systems. Deaths are reported within post-flood event reporting. The greatest burden of ill health from flooding is likely to be due to the long term impacts on mental health. Flooding increased the risk of mental disorders (anxiety and depression) and PTSD (post-traumatic stress disorder) in people whose homes have been flooded and who experienced disruption as a result of flooding (Waite *et al.*, 2017). The impact on mental health is formally recognised as an intangible loss and valued at 20% of the direct residential damages from flooding (Sayers *et al.*, 2020a).

Qualitative research on flooded communities has also shown that flooding can have both positive and negative effects on community cohesiveness with implications for how to maintain the resilience of communities (Walker-Springett *et al.*, 2017).

Flooding has major implications for local economies in terms of damage to households and commercial properties, and potential closure of individual companies (with some micro/small businesses never reopening) and impacts for future insurance premiums. ABI indicated that insurance claims resulting from the 2015-16 floods were around £1.3 billion. Future insurance premiums can also be affected for properties that are not covered by the Flood Re insurance scheme.

Disruption includes households and communities not directly flooded but experiencing the practical challenges resulting from disruption to utilities, transport infrastructure and local services; this is explored further in Chapter 4 (Jaroszweski, Wood and Chapman, 2021) and Risks H12 and H13.

Around 28 percent of caravan and camping sites (permanent and non-permanent) in England and Wales are at flood risk from rivers and the sea, with over two-thirds of these being at either significant (1 in 75 years or 1.3% AEP) or moderate flood risk (between 1 in 75-years and 1 in 200-years or 1.3% AEP and 0.5% AEP) (Defra, 2012a).

Since CCRA2, there have been a number of flood events with the most significant incidents occurring in August 2017, May 2018, June 2019, November 2019, February 2020 (Storm Ciara and Storm Dennis), December 2020 (Storm Bella) and January 2021 (Storm Christoph). Over 10,000 properties

were flooded during these events across the UK (Table 5.13), causing a significant number of people to be displaced from their homes for more than 6 months.

**Table 5.13.** Flood events across UK Source: Environment Agency, Department for Infrastructure (DfI) Northern Ireland, Scottish Environment Protection Agency (SEPA), NRW

Event/date	No. properties flooded	Location
August 2017	400	Northern Ireland - Foyle and Faughan River Catchments
May 2018	520	England - South East, Midlands
October 2018	302	Wales – Lampeter, Llanybydder, Llechryd, Carmarthen, Newcastle Emlyn, Llandysul
June 2019	380	England - East, Midlands, South East
November 2019	1,100	England - Yorkshire, Northern England
Storm Ciara – Early February 2020	1,350	England
	224	Wales
Storm Dennis – Mid February 2020	1,570	England
	160	Scotland
	2,765	Wales
Late February 2020	520	England
Storm Jorge – February/March 2020	141	Wales
Unnamed convective storm – August 2020	Over 190	Central and Eastern Scotland
Storm Francis August 2020	55	Northern Ireland - County Down near Newcastle and Draperstown, County Londonderry – Derry and Strabane
Storm Bella December 2020	400	Across England
	70	Dinas Powys, South Wales
Storm Christophe January 2021	675	Northern and Central England

#### 5.4.1.1.2 Current risk – England

The EA's Annual Flood and Coastal Erosion Risk Management report (2018/19) for England identifies that there are 2.5m properties at risk of flooding from rivers and the sea, 3.2m at risk of surface water flooding and 660,000 properties at risk of all three<sup>3</sup> for a 1 in 1000-year return period or 0.1% AEP. In addition, between 122,000 and 290,000 properties are at risk of flooding from groundwater – these properties may also be at risk of surface water flooding (EA, 2019b). It is important to note that most flood risk management activities aim to reduce flood risk but recognise that it is not possible to eliminate it completely – there is always an element of residual risk. Therefore, it is unlikely that these totals would decrease significantly over time.

<sup>3</sup> Notes: properties identified in the combined category are also included in the individual categories for river, sea and surface water flooding

Direct damages (EAD) from flooding in England for residential properties are currently around £291.3 million (all sources of flood risk), which equates to a high magnitude score.

Estimates of the economic losses from the winter 2019/20 flooding are around £333 million (all losses, not just residential), but the economic damage avoided from the protection provided is at least 14 times greater (EA, 2020e). The Environment Agency estimates that the economic damages from the winter 2015-16 floods in England were £1.6 billion, with £350 million related to residential damages (EA, 2018b). This is similar in scale to the 2013-14 winter floods, which had estimated economic damages (all losses) of £1.3 billion (EA, 2016c). The summer 2007 floods remain the largest in terms of economic damages (all losses), at an estimated £3.9 billion (EA, 2018a).

Evidence of the mental health impacts of flooding has increased since CCRA2 (2017) as the English National Study of Flooding and Health has reported results, including three years of follow up (PHE, 2020a).

The key findings of the research, funded by Public Health England (PHE, 2020a), include:

- The prevalence of probable depression amongst those whose homes were flooded was 20.1%, anxiety 28.3% and PTSD 36.2%. This compares with the general prevalence of depression amongst adults in Great Britain of 10% in 2019/20 (pre-COVID-19 pandemic) (ONS, 2020a).
- Three years after flooding, the prevalence of negative mental health outcomes in affected persons is reduced but still significant (Mulchandani *et al.*, 2020).
- Evacuation and displacement, particularly without warning, increases the risk of anxiety and post-traumatic stress disorder (Munro *et al.*, 2017).
- Factors that increase the risk of adverse mental health impacts include loss of utilities and problems with insurance.
- Many people experience persistent flood-related damage to their homes and this is associated with worse mental health outcomes (Mulchandani *et al.*, 2020).

There is also evidence that children's mental health is severely affected by flooding and the subsequent loss of familiar surroundings and friends, as well as witnessing the stress and strain affecting adults. This highlights the importance of policy responses considering the impacts for all affected groups (Mort *et al.*, 2016). Further, the research on mental and physical health risks is relevant for all parts of the UK.

#### 5.4.1.1.3 Current risk - Northern Ireland

The Northern Ireland Flood Risk Assessment (NIFRA) (2018) estimates that just over 25,000 or approximately 3% of the 861,000 properties in Northern Ireland are located within the 1 in 100-year (1% AEP) fluvial floodplain or 1 in 200 year (0.5% AEP) coastal floodplain (Department for Infrastructure, 2018). In addition, the surface water flood map indicates that around 24,500 or 3% of properties in Northern Ireland are sited in areas shown to be at risk of flooding from a 1 in 200-year (0.5% AEP) surface water event with a depth greater than 300 mm. Overall, approximately 45,000 or 5% of the properties in Northern Ireland are located within either the 1% AEP fluvial floodplain or in areas at risk of flooding from a 0.5% AEP surface event with a flood depth greater than 300 mm

(Department for Infrastructure, 2018). Note that this is less than the total sum of properties affected by flooding from rivers or surface water, as some properties are at risk from both sources.

Direct EAD from flooding in Northern Ireland for residential properties are currently around £21.3m (Sayers *et al.*, 2020a), which equates to a high magnitude score. The Department of Infrastructure, Northern Ireland Executive estimated that the clean-up costs of the August 2018 floods exceeded £30m.

#### 5.4.1.1.4 Current risk - Scotland

The National Flood Risk Assessment for Scotland, 2018 estimates that 284,000 properties are at risk of flooding (1 in 200-year return period or 0.5% AEP) (SEPA, 2018). At least some of these may be properties constructed since 1<sup>st</sup> January 2009 and are therefore not eligible for insurance through the Flood Re scheme (Scottish Government, 2015b).

Direct EAD from flooding in Scotland for residential properties are currently just over £68.5m, which equates to a high magnitude score. Estimates of the cost of flood damages to property (all types and including indirect costs) in Scotland vary from £200m to £250m per year. The storms of early 2016 were estimated to have cost the Scottish economy £700m.

A three year study of flood-affected communities in Scotland identified mental health impacts for people affected by flooding resulting from the long-term use of temporary accommodation, and sustained involvement in the reinstatement or refurbishment of their own properties. Further upset and anxiety arose from flood-related experiences and frequent communications with insurance companies and associated parties, and dealing with unforeseen costs (Currie *et al.*, 2020).

#### 5.4.1.1.5 Current risk - Wales (H3)

Across Wales over 245,000 properties are at risk of flooding from rivers, the sea and surface water (Flood Risk Assessment Wales, Natural Resources Wales (NRW) 2019) at a return period of 1 in 1000 years (0.1% AEP).

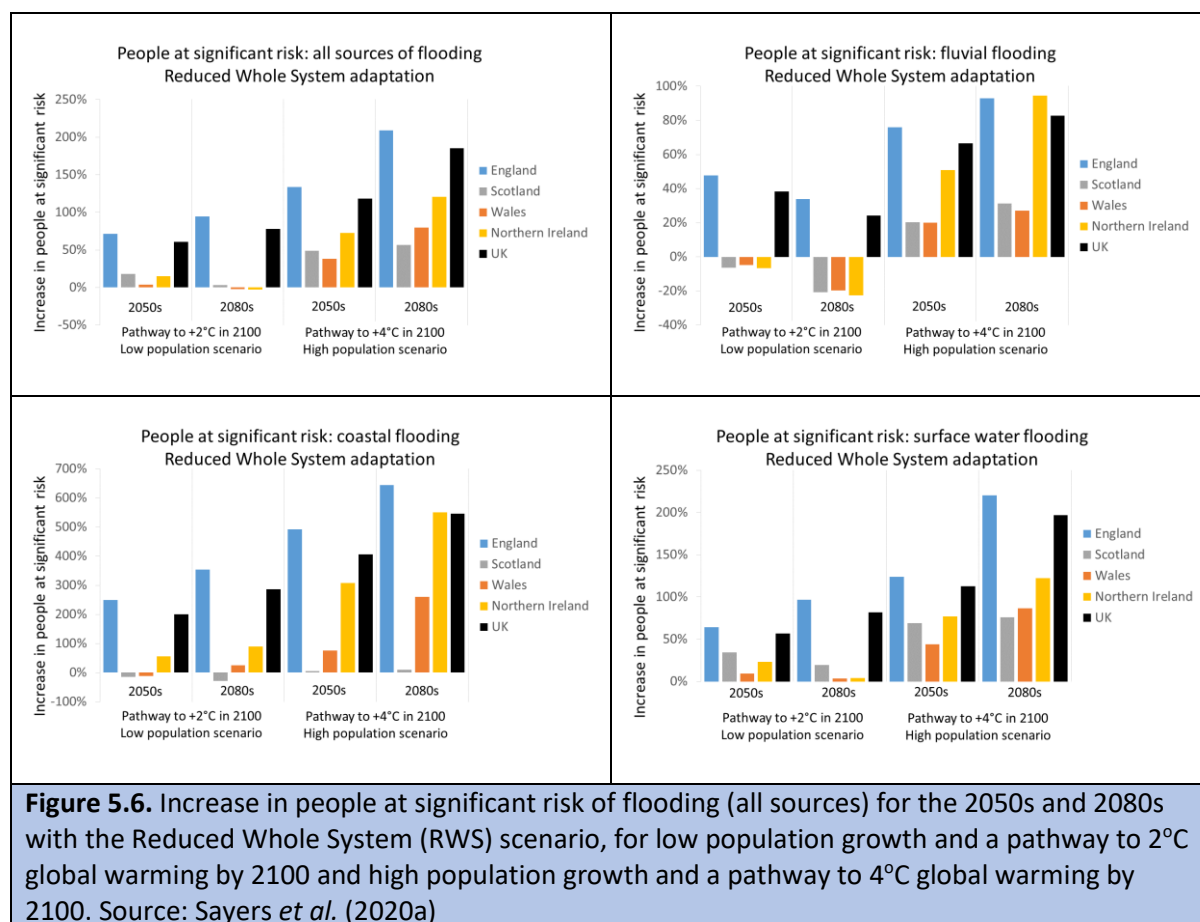
Flooding in February 2020 across Wales resulted in the flooding of 3,130 properties. The month was recorded as the wettest February since records began in 1862. During Storm Dennis, 22% of NRW's river gauges recorded their highest water levels ever. NRW's flood review of the February storms found that many structures and systems worked well and as expected to protect thousands of properties across Wales from the impacts of the extreme rainfall (NRW, 2020b). Yet the scale and speed of the rainfall was such that some flooding was unavoidable, resulting in considerable long-term impacts on individuals and communities.

EAD from flooding in Wales for residential properties are currently around £94.5m, which equates to a high magnitude score. Flooding in Wales cost an estimated £71 million between November 2011 and March 2014 (NRW, 2015). The wider costs of flooding include to defences. For example, an estimated £8.1m of damage was caused to coastal defences in Wales during the storms in December 2013 and January 2014 (NRW, 2014a).

## 5.4.1.2 Future risks – UK (H3)

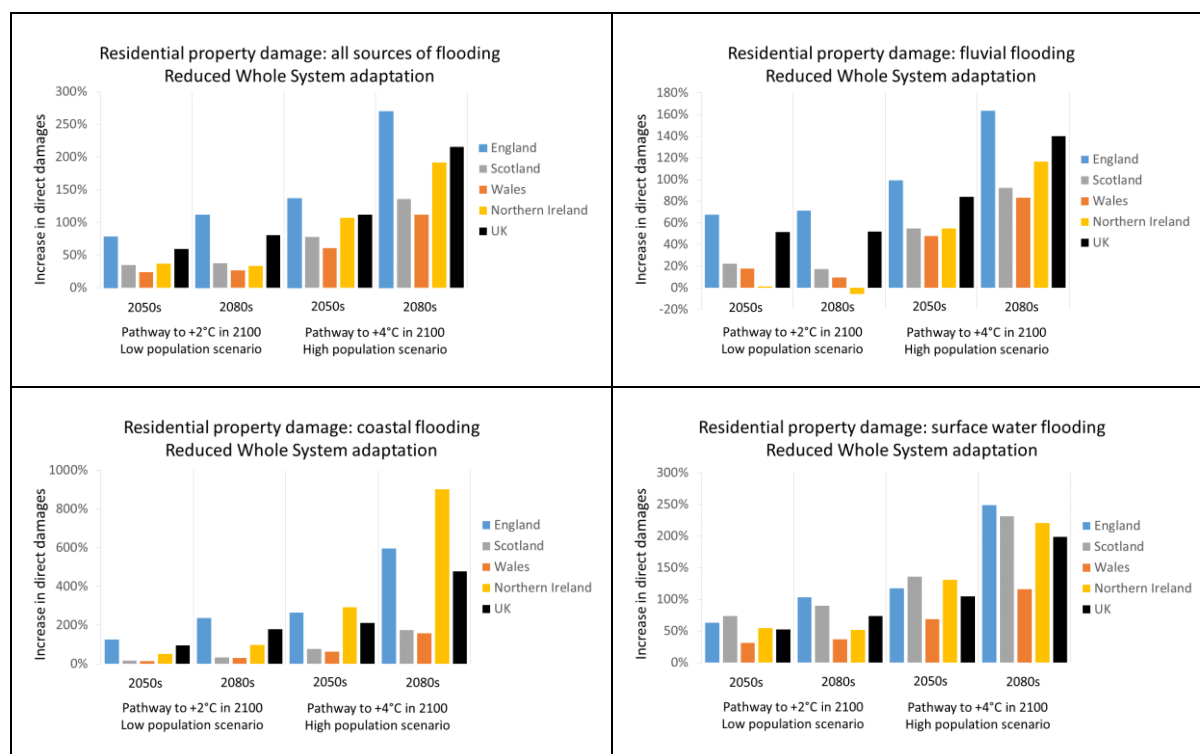
Climate change is projected to increase the number of properties at risk of flooding, from all sources, and including in areas that have not previously been at risk of flooding (Sayers *et al.*, 2020a). In addition to climate change, housing need and economic growth requiring more development are also projected to exacerbate flood risk (Table 5.2). Strategies to avoid increasing the population at risk of flooding include: (i) minimising new building in areas at risk of flooding; (ii) ensuring that such properties incorporate appropriate resilience and/or resistance measures; and (iii) installing sustainable drainage design for the lifespan of the development (Rowland *et al.*, 2019).

Figures 5.6 and 5.7 detail the projected increase in the number of people at significant risk (1 in 75-years or 1.3% AEP) and in EAD for residential properties (direct costs only) for the 2050s and 2080s for scenarios of 2°C and 4°C global warming by 2100 and low and high future population growth scenarios for the reduced whole system (RWS) adaptation scenario for England, Northern Ireland, Scotland and Wales<sup>4</sup>.



<sup>4</sup> The RWS scenario is used as this relates to 'no additional action'. It is not the 'do nothing' scenario but assumes minimum intervention. Some of the percentage changes shown in the table under low population scenarios are negative, meaning that risk could reduce. This is because in the low population scenarios the population is decreasing in some nations, so by the 2080s in particular that causes an overall reduction in risk. Alongside this, the RWS scenario is equivalent to a 'low effort' scenario but not a 'no adaptation' scenario so population reduction and minimal adaptation 'cancel out' any potential increase in risk from climate change.





**Figure 5.7.** Increase in EAD (direct residential damages) for the 2050s and 2080s with Reduced Whole System (RWS) adaptation, for a pathway to 2°C global warming by 2100 with low population growth, and a pathway to 4°C global warming by 2100 with high population growth. Source: Sayers *et al.* (2020a)

England accounts for the greatest increase in the number of people at significant risk of flooding (and has the largest baseline) for all climate futures and sources of flooding, other than for fluvial flooding in the 2080s with a +4°C, high population future where Northern Ireland has a higher proportionate increase (noting that the latter's baseline is just under 10,000 people compared with almost 476,000 for England). Current risk is most prevalent for surface water flooding and therefore future increases here result in substantial numbers at risk. However, the impacts for households are generally lower for surface water flooding compared with river and sea flooding due to the depths and velocities involved.

Decreases are shown in the numbers of people at significant risk of fluvial flooding in the 2050s and 2080s for Scotland, Wales and Northern Ireland in the low population scenario, which is due to estimated decreases in population living in areas at significant risk from fluvial flooding, cancelling out the effects of climate change in the scenario of 2°C global warming by 2100.

Coastal flooding accounts for the greatest increases with England and Northern Ireland showing four, five and six fold multiples of the current population at significant risk.

Regarding potential damages, under a 4°C (increase in Global Mean Surface Temperature (GMST)) future with high population growth, there is likely to be a rapid increase in damages to the 2050s and then on into the 2080s. Most present day and future flood risk is in England with direct residential EAD projected to rise by 137% by the 2050s and 269% by the 2080s under a pathway to

4°C global warming by 2100 and a high population scenario. Note these future values only consider population growth; they do not include allowance for economic growth and the associated increase in value at risk, and thus will likely underestimate actual future damages. When risks are normalised by the flood exposed population (the average EAD per individual) then a different picture emerges, with those living in flood risk areas in Northern Ireland, Scotland and Wales exposed to a higher EAD than those in England. This has implications for adaptation.

At the local level, the largest future flood risk is evident in coastal areas including the top three risk locations of Hull, the City of Portsmouth and Sedgemoor District Council (noting that planned flood risk alleviation measures are not taken into account). In some locations, the influence of climate change on flood risk is much less, including areas at risk of fluvial flooding where decreased peak flows are expected.

When future flood risk is mainly driven by climate change, rather than population increase, this influence is felt most keenly in coastal areas. By the 2080s the combination of a climate change scenario of 4°C global warming by 2100 and high population growth with no additional adaptation action leads to an increase in direct EAD for residential properties of around £1.5 billion; including indirect damages would bring this to around £2.9 billion. This bleak future requires both adaptation and mitigation activity to prevent its realisation (Sayers *et al.*, 2020a).

#### 5.4.1.3 Lock-in and thresholds (H3)

Lock-in will arise if development in flood risk areas is not resilient to current and future flood risk and where flood risk management measures are currently, or will become, insufficient to manage the risk. There is also the potential for lock-in to occur through local plan allocation, although this should be avoided through the use of up to date local authority-wide strategic flood risk assessments (SFRAs) that take account of climate change.

New development in areas at highest river and coastal flood risk (Flood Zone 3b – the functional flood plain) in England increased from 7% of all new development in 2013/14 to 9% in 2017/8 (17,580 properties). It should be noted that the Environment Agency flood zones do not take account of existing defences such as the Thames Barrier. If this 7–9% range continues from 2018/19 until 2022/23, and the Government meets its target to build 300,000 new homes in England per year, then between 105,000 and 135,000 more homes could be built in Flood Zone 3b in total over the five-year period (CCC, 2019b). Similar figures are not available for the devolved administrations. It is possible that properties could move to a higher risk flood zone as a result of climate change, but climate change allowances are built into planning policy guidance.

Planning policies permit development in areas at risk of flooding providing floor levels are raised, and/or household resistance or resilience measures are incorporated (resistance measures prevent water entering a building whilst resilience measures aim to minimise damage once water has entered). Planning applications for development in areas at risk of flooding need to be supported by independent evidence that flood risk from all sources, including surface water, has been assessed and mitigated and takes account of the implications of climate change.

The risk of surface water flooding is likely to increase with climate change and increased intensity/frequency of precipitation as well as declining urban greenspace. Data available for England show greenspace has declined from 63% of urban areas in 2001 to 55% in 2018 (CCC, 2019b). The proportion of impermeable surfacing in towns and cities, which can increase flood risk, has risen by 22% since 2001 (CCC, 2019b). However, the 25 Year Environment Plan has targets to reverse this and increase urban greenspace (Defra, 2018b) and policy initiatives such as the requirement for Biodiversity Net Gain linked to planning permission should also help.

Lock-in will also be affected by the extent to which flood risk management measures are adequately maintained to withstand flooding. Recent research conducted by the Environment Agency suggests that current budgets for maintenance and repairs may need to increase annually by between 30% and 80%, some £30 million to £75 million per year, to address the greater potential for deterioration (EA, 2020c). In addition, upgrading and improvements will be needed for the most affected assets. This research focuses on England, but it is likely that the devolved administrations will also face considerable increased maintenance costs to address future deterioration and the need for increased protection as a result of climate change.

Thresholds are likely to vary by time and place depending on the state of the assets, levels of investment to address climate change risks and/or maintain or improve the state of the assets, and the changing level of risk spatially over time. Raising defences will become technically and socially challenging with climate change, and will involve increasing costs to provide the same levels of absolute protection (e.g. to a 1 in 75-year event). This may challenge the long-term sustainability of Flooding and Coastal Erosion Risk Management (FCERM) assets. Whilst flood defences can be refurbished, there are thresholds (which vary by defence type) which if exceeded mean defences require full re-engineering.

An unknown policy related threshold is the extent to which the expected withdrawal of Flood Re in 2039, and return to fully risk reflective pricing for household insurance, could affect housing markets, particularly as extreme events are expected to increase. This would dramatically impact on insurance affordability, with projections of rising unaffordability across many areas of the UK. However, part of Flood Re's purpose is to plan for the return to a risk reflective market and its Quinquennial Review (QQR) sets out proposed changes to the scheme to enable and accelerate the transition process (Flood Re, 2019).

#### 5.4.1.4 Cross-cutting risks and interdependencies (H3)

Interactions are evident between levels of flood risk and the wider socio-economic context. Meeting housing development targets in areas that are not at flood risk and without increasing flood risk elsewhere will continue to be a challenge. There may be interactions between flood risk and risks to the economy if there is a destabilising effect on housing markets in future (though this remains unclear). Increasing social vulnerability, for example, due to an ageing population and potential changes in poverty rates, may exacerbate the negative impacts of flooding for health and wellbeing. Flood risks are also considered within other risks in this chapter:

- Risk H4 on coastal risks

- Risk H5 on risks to building fabric
- Risk H11 on risks to cultural heritage
- Risk H12 on risks to health and social care delivery
- Risk H13 on risks to schools and prisons

Flood risks are also described in Chapters 3 (Watkiss and Betts, 2021), 4 (Jaroszweski, Wood and Chapman, 2021), 6 (Surminski, 2021) and 7 (Challinor and Benton, 2021) in this report. Failure to adapt in these sectors, e.g. to address risks to infrastructure, will have cascading social impacts, for example, bridge closures may prevent people getting to work or children to school. A combination of flooding and electricity failures can disrupt services to people in hospitals and care homes and in receipt of home care (see Chapter 4: Jaroszweski, Wood and Chapman, 2021).

#### 5.4.1.5 Implications of Net Zero (H3)

The UK Net Zero target in itself is not likely to increase or decrease the level of flood risk across the UK. However, management of the risk could have an impact on the target. Flood defences have high embodied carbon, and thus could be a factor for a Net Zero transition. The Environment Agency has developed a Carbon Planning Tool to assess carbon over the whole life of built assets aiming to make carbon part of the decision making process throughout the delivery cycle of its assets (EA, 2016a). Application of this tool suggests that across the whole flood risk management programme between 40,000 and 84,000 tCO<sub>2</sub>e<sup>5</sup> (27–57% of total capital/construction carbon emissions) could be saved by using low carbon materials and approaches (Mott McDonald, 2018). Natural Resources Wales is in the process of implementing the use of the same carbon planning tool and in Scotland, there is a requirement under the 2019 Planning (Scotland) Act to understand the impact of lifecycle greenhouse gas emissions of national development on meeting emissions reductions targets. There is no evidence of similar requirements in Northern Ireland.

In addition, NFM has the potential to sequester substantial amounts of carbon, particularly if undertaken on a large scale involving woodland planting, soil carbon improvements and land use change. The use of SuDS where these involve an increase in blue/green infrastructure, noting that some use structural solutions such as underground concrete storage, also provide the opportunity to enhance shading and cooling, and sequester carbon. The Working with Natural Processes Evidence Directory provides some case study examples, such as how creating an extra 50 ha of floodplain (Norfolk Broads) provides £1 million carbon sequestration benefits and £27 million recreational value over 100 years (EA, 2018e).

The Net Zero agenda also provides an opportunity for the retrofit of properties to improve energy efficiency in combination with enhancing flood resilience. This requires increasing awareness amongst property developers and estate managers as well as upskilling within the construction industry regarding the management of moisture and flood risk.

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<sup>5</sup> tCO<sub>2</sub>e: mass of all anthropogenic greenhouse gases expressed as the equivalent mass of CO<sub>2</sub> in tonnes that would produce the same climate forcing

#### 5.4.1.6 Inequalities (H3)

Research conducted in 2017 regarding Present and Future Flood Vulnerability, Risk and Disadvantage (Sayers *et al.*, 2017a) highlighted significant variation in flood disadvantages across the UK. Flood disadvantage is a combination of geographic disadvantage (living in an area at flood risk) and systemic flood disadvantage (the degree to which socially vulnerable communities are disproportionately affected by flooding). Ten local authorities account for 50% of the socially vulnerable people living in at areas at flood risk; these are Hull, Boston, Belfast, Birmingham, East Lindsay, Glasgow, Leicester, North East Lincolnshire, Swale District and Tower Hamlets. Coastal areas, declining urban cities and dispersed rural communities are highlighted as representing the greater concentrations of flood disadvantage. When income and insurance penetration are considered, the Relative Economic Pain (ratio between uninsured loss and income) is significantly higher in vulnerable communities than elsewhere. In addition, sea level rise will impact disproportionately on disadvantaged coastal communities, which is investigated in further detail in Risk H4.

In many rural towns and villages and smaller urban cities and towns, the most socially vulnerable communities are exposed to higher flood risk, on average, than those that are less vulnerable. In rural towns and fringes in sparse settings the present day EAD is around £150 per person in flood risk areas, but rises to £280 for the most socially vulnerable neighbourhoods. This trend continues into the future, but it is socially vulnerable neighbourhoods in urban cities and towns that are likely to experience the most disproportionate increase in risk, with EAD per person increasing by an average factor of 2.8; this figure falls to 2.5 for the whole population (Sayers *et al.*, 2020a).

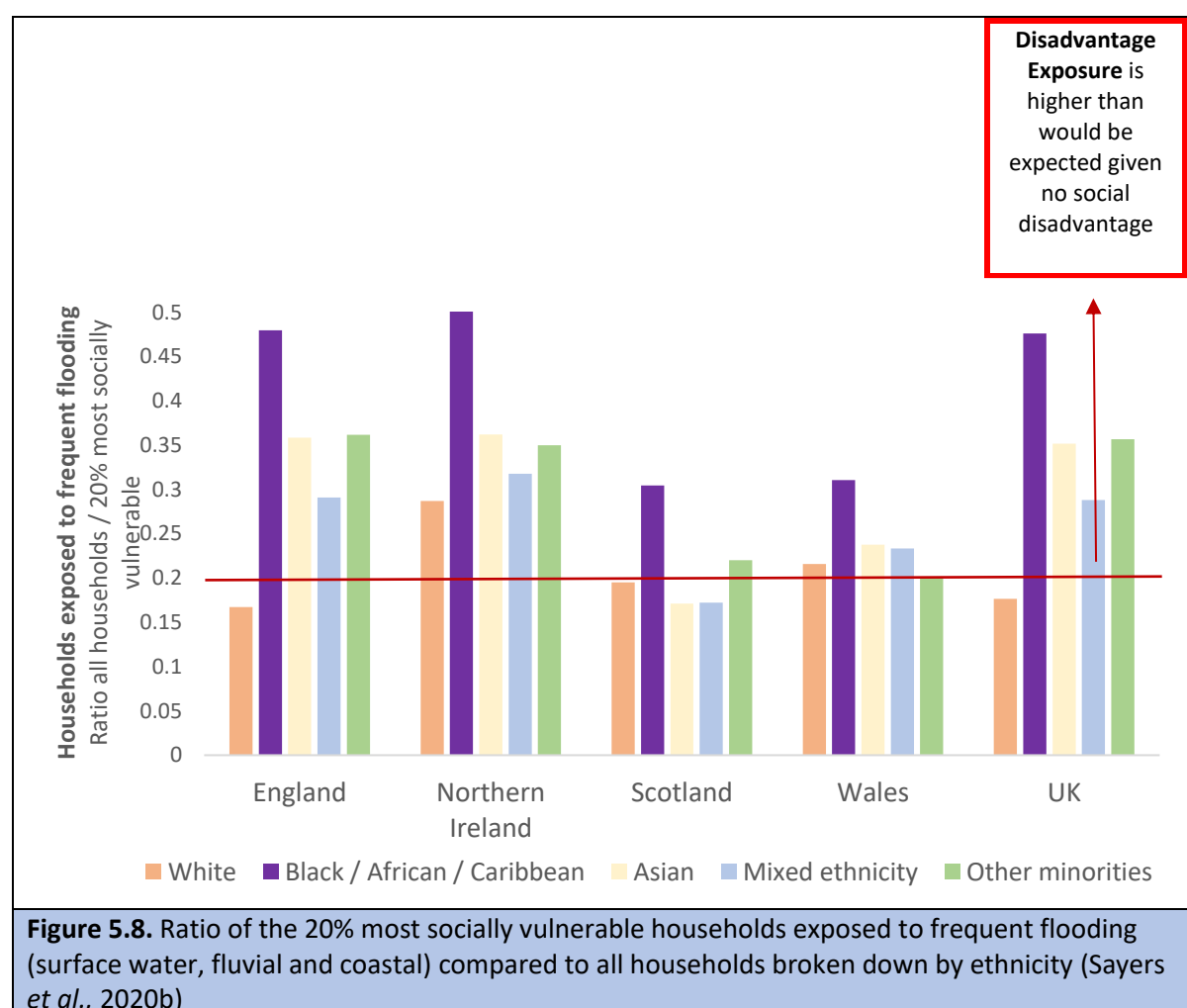
Housing developments in areas prone to frequent coastal and surface water flooding (1 in 75-years or more frequent) across the UK have disproportionally taken place in the most vulnerable neighbourhoods. By the 2080s, while all these developments are expected to experience a significant increase in exposure to flooding across all sources, the increase is greatest in those developments built in the most vulnerable neighbourhoods, particularly at the coast (Sayers *et al.*, 2017b). The report which set out this finding did not consider the implications of erosion enhanced flooding and therefore the number of properties affected on the coast may be larger.

At the national scale, social disadvantage measured through Relative Economic Pain is greater in Northern Ireland, Scotland and Wales than in England. There is also considerable spatial variation within countries due to the lower penetration of insurance in the most socially vulnerable neighbourhoods compared to others which, when combined with lower household incomes and exposure to more frequent flooding, leads to significant disadvantage.

The wider social impacts of flooding are increasingly being quantified for particular flood events and encompass lack of access to services, including health and social care, loss of school and workdays, travel disruption and displacement from home, sometimes for prolonged periods (Szönyi *et al.*, 2016). All income groups are at risk of adverse consequences, but lower income households may suffer more severe adverse effects, particularly as they have less resources for coping in the short term and long-term recovery from the impacts (Sayers *et al.*, 2017b).

Socio-economic status and pre-existing health conditions are recognised as factors that increase the risk of adverse outcomes from flood events. Risk perception and coping capacity also affect the ability of communities to prepare for and manage flood risk (Rufa *et al.*, 2015).

Research has recently been published by Flood Re regarding geographic flood disadvantage and systemic flood disadvantage now and in the future with a focus on Black, Asian and Minority Ethnic communities (Sayers *et al.*, 2020b). The analysis reveals that the most socially vulnerable of all ethnicities experience systemic flood disadvantage (experiencing risk that is greater than the average), with Black, African and Caribbean Ethnic Groups particularly disadvantaged (Figure 5.8) (Sayers *et al.*, 2020b). It also reinforces previous findings that those living in rural towns, smaller urban settlements, and at the coast often experience more frequent flooding than others.



#### 5.4.1.7 Observations regarding the impact of COVID-19 (H3)

Pandemic response measures will affect households displaced by flooding in 2020 and 2021. Social distancing is challenging in evacuation situations, increasing the chance of infection. It is too early to assess the mental health implications of the combined affect of flooding and the pandemic.

It is likely to be the time and resources required by local authorities and other risk management authorities to conduct emergency planning to manage the virus and its implications that leaves less resources available for flood risk management. This includes diverting officers from usual day-to-day duties to emergency planning due to the scale of the impacts. Obtaining contributions to match Government funding for flood risk management schemes is also likely to become more challenging as both public and private sector organisations will have far less resources available.

#### 5.4.1.8 Magnitude Scores (H3)

Current risk is considered to be high for all countries of the UK based on national flood risk assessments and the Future Flood Risk Research Project with EAD currently all at a high level across the UK. Future risk is similarly high across the UK; confidence for both is high due to multiple sources of evidence highlighting the severity and extent of flood risk for health, communities and the built environment.

**Table 5.14.** Magnitude scores for risks to people, communities and buildings from flooding

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	High  (High confidence)	High  (High confidence)	High  (High confidence)	High  (high confidence)	High  (High confidence)
<b>Northern Ireland</b>	High  (High confidence)	High  (High confidence)	High  (High confidence)	High  (High confidence)	High  (High confidence)
<b>Scotland</b>	High  (High confidence)	High  (High confidence)	High  (High confidence)	High  (High confidence)	High  (High confidence)
<b>Wales</b>	High  (High confidence)	High  (High confidence)	High  (High confidence)	High  (High confidence)	High  (High confidence)

## 5.4.2 Extent to which current adaptation will manage the risk (H3)

### 5.4.2.1 Effects of current adaptation policy and commitments on current and future risks (H3)

#### 5.4.2.1.1 UK-wide

There are four main strategies for addressing flood risks which are discussed for each UK country, other than insurance which is discussed at the UK level.

- Planning policy and guidance to minimise new dwellings and assets in flood risk areas.
- Flood risk management policy, investment and interventions, including:
  - Structural measures
  - Natural flood management (NFM) and Sustainable Drainage Systems (SuDS)
  - Property flood resilience (PFR)
- Emergency planning and preparedness.
- Flood insurance provision.

HM Government's National Risk Register, 2020 identifies coastal and river flooding as the two highest impact risks facing the UK after pandemics and large scale Chemical, Biological, Radiological and Nuclear attacks. It is not known whether consideration is yet being given to whether climate change is beginning to change the risk profile for major flood events in the national assessment.

Planning policy is a devolved issue and therefore differs across the UK at the national and local levels including measures put in place to manage and alleviate flood risk. Flood risk management policy and investment is also a devolved issue. Key flood risk management interventions include structural measures, natural flood management (NFM), and property flood resilience (PFR). NFM involves the use of natural processes to help alleviate flood risk (see Chapter 3: Berry and Brown, 2021) and can complement other structural defences. PFR requires a package of measures, some of which prevent water entering the property (resistance measures) e.g. flood doors, and others that minimise the impact should water enter the house (resilience measures) e.g. using flood proof plaster, or other measures to speed up the recovery process.

Given that policies and plans related to planning, flood risk management investment and emergency preparedness are devolved, they are covered for each UK nation below. Insurance is applied UK-wide and covered at the end of this sub-section.

#### 5.4.2.1.2 England

##### 5.4.2.1.2.1 Planning policy

The National Planning Policy Framework (NPPF) states that local plans should take a proactive approach to mitigating and adapting to climate change, taking into account the long-term implications for flood risk, coastal change, water supply, biodiversity and landscapes, and the risk of overheating from rising temperatures. In addition, Planning Practice Guidance (PPG) provides



detailed guidance for developers and planners regarding flood risk assessment to avoid development in areas at flood risk, and the Environment Agency is a statutory consultee to all applications for development that could be at current risk of flooding from rivers and the sea or are in a critical drainage areas. It is important to note that guidance regarding climate change allowances for new development includes sensitivity testing up to an extreme H++ scenario (EA, 2016d).

In 2019/20, 96% of planning applications were determined to be in line with the Environment Agency's flood risk advice and 98% of new homes included in planning applications were determined in line with the Agency's advice. There is no evidence regarding the degree to which conditions regarding the resilience of development in areas at greatest flood risk (Flood Zone 3) have been met, however.

SuDS policies vary in local plans with differing levels of prescription on their use and examples of policies being either strengthened or weakened at examination stage by the Planning Inspectorate. Where weakened, this included removing references to 'multi-functional' benefits, adding 'feasibility' caveats and removing references to the green infrastructure role of SuDS from 'bold type' policy (TCPA, 2016).

In 2018, the Ministry of Housing, Communities and Local Government conducted a review of the application and effectiveness of planning policy for SuDS (MHCLG, 2018). This concluded that current arrangements for SuDS in planning have been successful in encouraging the take-up of sustainable drainage systems in a cross-section of new developments with almost 90% of all approved planning applications sampled featuring SuDS. The review concluded that whilst national planning policy has a clear role to play in facilitating the delivery of SuDS, other factors, such as arrangements around sharing good practice and innovation, can also influence their uptake in new developments. The review's evidence was informed by a survey of adopted and emerging local plans and adopted Supplementary Planning Guidance from all 338 Local Planning Authorities (LPAs) in England.

However, evidence for the implementation of planning policy was obtained from just twelve LPAs and their respective Lead Local Flood Authorities (LLFAs), so may not be representative. Following the review, the National Planning Policy Framework was updated in 2019 to include stronger wording on sustainable drainage (MHCLG, 2019a). It is not yet clear what impact this is having at the local level. There is also concern about the extent to which green as opposed to grey SuDS are being used in practice, as data are not available on actual levels of uptake (CIWEM, 2016; TCPA, 2016).

#### 5.4.2.1.2.2 Flood risk management policy and investment

In England, there are various plans to tackle different sources of flooding and increasingly these are more holistic and long-term, helping to overcome previous concerns regarding the lack of a statutory, long-term strategy that addresses the likely climate change risks, and their differing time and spatial scales (CCC, 2019b).

In 2020, Defra published a Policy Statement on Flood and Coastal Erosion Risk Management. This sets out the government's long-term ambition to create a nation more resilient to flood and coastal

erosion risk with key objectives to upgrade and expand national flood defences and infrastructure, manage the flow of water more effectively, harness the power of nature to reduce flood and coastal erosion and achieve multi-benefits, better prepare communities, and enable more resilient places through a catchment-based approach. The policy statement, supported by additional funding for flood and coastal erosion risk management, states that every area of England will have a more comprehensive local plan that drives long-term action and investment.

The National Flood and Coastal Erosion Risk Management (FCERM) Strategy (2020) updated and published by the Environment Agency sits alongside the Policy Statement and has a vision of '*a nation ready for, and resilient to, flooding and coastal change – today, tomorrow and to the year 2100*' (EA, 2020e). The strategy strongly promotes a shift from protection to resilience through a basket of measures and describes what needs to be done by all risk management authorities (RMAs) involved in FCERM for the benefit of people and places. It also promotes the use of adaptive pathways that enable local places to better plan for future flooding and coastal change and adapt to the future climate. All FCERM activities conducted by RMAs, including plans and strategies, must be in alignment with the Strategy. Long-term delivery objectives are set out that should be implemented over the next 10 to 30 years. It also includes shorter term, practical measures RMAs should take working with partners and communities. The strategy has a greater focus on addressing climate change than the previous version with its three objectives being (i) climate resilient places; (ii) today's growth and infrastructure resilient in tomorrow's climate; and (iii) a nation ready to respond and adapt to flooding and coastal change.

In 2020, alongside its new Policy Statement and Strategy, the UK Government announced that it would double its current capital investment in flood and coastal defences in England to £5.2 billion over the next six years – 2021–2027. This doubling was comparing with £2.6 billion in the funding programme from 2015–2021 (Defra, 2020b). The new investment is intended to ensure that a further 336,000 homes and non-residential properties such as businesses, schools and hospitals are better protected from flooding and coastal erosion. The investment also aims to avoid the disruption caused by flooding to the daily life of over 4 million people, avoid £32 billion of wider economic damages, create or improve 5,440 ha of natural habitat, and enhance 830 km of rivers.

The Government's previous FCERM investment programme has improved protection for 242,343 homes between April 2015 and April 2020 in England, in line with its target to provide better protection for 300,000 homes by 2021. A review conducted in 2017 (Wingfield and Brisley, 2017) focused on those schemes that accounted for a large proportion of the homes better protected. This revealed that based on an improved Standard of Protection (SoP), most of the schemes were taking households from very significant risk to low or moderate risk - the schemes assessed were improving the SoP for households. Furthermore, most of the schemes were increasing the existing SoP and incorporated an increase in risk due to climate change in the design. The Environment Agency's National Flood Risk Assessment (NaFRA) estimates that EAD Annual Damages avoided (properties and public infrastructure) from rivers and sea (annually) is £664 million (EA, 2018d).

The long-term investment scenarios (LTIS) are an economic assessment showing what future FCERM could look like over the next 50 years in England. LTIS sets out the total national level of investment if there is investment in all the places where the benefits are greater than the costs; the optimum

level of FCERM investment. LTIS estimates that the overall economic optimum level of investment to reduce the risk from climate change is a long-term annual average of over £1 billion (EA, 2019c). LTIS uses NaFRA for the risk of flooding from rivers and the sea. NaFRA was updated in 2018 and provides a new estimate of present day expected annual damages (EAD). The output for NaFRA is also one of the input datasets used by the Future Flood Explorer (FFE) model to estimate future projections of flood risk (Sayers *et al.*, 2020a). The representation of climate change, population growth and adaptation are represented differently (to a greater or lesser extent depending on the specific combination of the three) in the FFE and LTIS.

A £200 million Flood and Coastal Resilience Innovation programme was announced in the 2020 Budget (HM Treasury, 2020). This aims to help meet the intended outcomes of the Government's Policy Statement and the National FCERM Strategy and will support projects in particularly vulnerable areas that demonstrate how practical, innovative action, such as NFM, SuDS, PFR and building the capacity of the community and voluntary sector to respond and recover, can work to improve resilience to flooding and coastal erosion.

The overall level of investment into flood defences in England will also include revenue investment (such as strategy and plan development, research and modelling, and emergency planning compared with capital investment in physical interventions), and contributions from others via the Partnership Funding process. Therefore, it is likely (but not yet determined) that the overall level of investment over the six years from 2021 will meet the required £1 billion per year identified by LTIS, allowing for faster progress towards the long term adaptation required (EA, 2019c).

In 2020, the Partnership Funding approach (the main public sector source of funding for FCERM interventions) was revised (Defra, 2020b) to better reflect the wider benefits that flood alleviation projects can facilitate. The changes include:

- updated payment rates to reflect inflation and new evidence on flood damages since 2011 (including people impacts such as mental health).
- a new intermediate risk band for moving properties and other assets between high and medium risk to help manage surface water flood risk, meaning more surface water schemes are likely to receive Defra grants in the future.
- improved payment rates for environmental benefits to better capture the wider environmental benefits achieved by some flood schemes and encourage environmentally beneficial design.
- recognition of the benefits for properties that will become at risk in the lifetime of flood defences due to the impacts of climate change.

Partnership Funding continues to prioritise investment to protect properties in deprived communities. Additional funding streams should also mean that more investment is available for flood risk management schemes that help to protect critical infrastructure such as schools, hospitals, roads and railways, and more money should be available to upgrade existing Environment Agency flood risk assets (EA and Defra, 2020).

Following the Flood and Water Management Act (FWMA) of 2010 (England and Wales), unitary authorities and county councils have become the Lead Local Flood Authority (LLFA) for their areas. A

Government-commissioned evaluation of the implementation of the FWMA found that the new strategy requirements had led to a more comprehensive understanding of local flood risk and to more proactive, coordinated management of this risk (Maiden *et al.*, 2017). All LLFAs now have strategies in place but no evaluation has been conducted regarding their effectiveness. Government has committed to work with the Environment Agency and LLFAs to develop new guidance on their local flood risk management strategies, which reflects the revised national strategy, shares best practice on content and use, and explains how they fit with other plans and strategies (Defra, 2018d).

Shoreline Management Plans (SMPs) aim to identify the most sustainable approach to managing the flood and erosion risks to the coastline in the short-term (0 to 20 years), medium term (20 to 50 years) and long term (50 to 100 years). SMPs are non-statutory documents that provide a broad assessment of the long-term risks associated with coastal processes, providing guidance to coastal engineers and managers to identify and recommend strategic and sustainable coastal defence policy options for particular lengths of coast to reduce these risks to people, the developed and natural environments. A SMP Refresh project is currently underway in England (and Wales) to review what has changed since SMP2 in terms of legislation, policy and climate projections and provide coastal groups with advice on how to take account of this in their SMPs. It does not constitute a fundamental review of all SMPs. Informed by the Environment Agency's current refresh of technical evidence supporting Shoreline Management Plans, national policy for Shoreline Management Plans will also be reviewed to ensure local plans are transparent, review outcomes and enable local authorities to make robust decisions for their areas.

#### 5.4.2.1.2.3 Flood risk management interventions

In England, NFM continues to be widely promoted by Government and can help schemes benefit from funding through the revised Partnership Funding formula in England (Defra, 2020b). Outcome Measure 4 (OM4) within the formula focuses on habitat and biodiversity enhancements and supports FCERM projects that reduce the risk of flooding and coastal erosion in ways that provide additional environmental benefits and support wider policies, including the 25 Year Environment Plan and the FCERM Strategy (2020) (Defra, 2018b; EA, 2020e).

Defra's Property Flood Resilience Action Plan (2016) is the main mechanism promoting PFR (BRE, 2016a). This aims within five years to achieve an *'environment where it is standard practice for properties at high flood risk to be made resilient'* and, within two years, to have made *'significant progress towards developing the systems and practices within the insurance, building and finance sectors that normalise the uptake of property level resilience within existing activity'* (BRE, 2016a). The plan does not quantify the number of properties or locations to target, and neither NAP2, nor Defra's Action Plan, quantify the ambitions for the role of PFR in managing vulnerability or offer a strategy to drive the large-scale implementation of these measures (CCC, 2019b). The Government Policy Statement set out government's commitment to further boost uptake of PFR in homes and businesses, and the new National Strategy on FCERM includes a strategic objective and associated measures to help mainstream PFR by removing the policy, financial and behavioural barriers, encourage building back better after flooding and increase the uptake of PFR in high-risk communities (EA, 2020e). Additional initiatives include £2.9 million extra funding from the 2018

budget, which is supporting three PFR pathfinder projects and the Flood and Coastal Resilience Innovation Programme (Defra and EA, 2019, 2021; EA, 2020g). Defra is (at the time of writing, April 2020) consulting on whether there is more that the Flood Re Scheme could do to accelerate uptake of PFR to support the transition to a risk reflective home insurance market for those at risk of flooding by 2039.

The CCRA2 Evidence Report reported only 3,174 properties taking up publicly funded property PFR measures in the reporting period to 2015, with 3,074 either planned or in the works for 2016–2021. Since April 2015, it is reported that a further 1,245 homes have implemented PFR measures, at a rate of around 415 properties per year (Ffoulkes *et al.*, 2019), slightly less than the 500 households per year proposed in the Government’s FCERM investment programme (CCC, 2019b). However, this reported data has limitations, as other centrally funded schemes, such as the PFR repair scheme, do not necessarily report how many properties are adapted and individuals may install measures independently. In addition, recovery grants issued following floods may or may not be used for property resilience works. It is therefore not possible to know accurate numbers of uptake, but these are likely to be higher than those quoted.

A UK-wide Code of Practice for PFR was launched in February 2020 and published in January 2021 (Kelly *et al.*, 2021) following years of work through the industry led PFR Round Table set up by Defra following the publication of the PFR Action Plan in 2016. The purpose of the code is to help individuals and businesses understand the practical measures they can implement and restore properties more quickly post flood events. It sets out a clear process and standards for PFR which should support increased take-up.

Continually increasing awareness of flooding amongst public and private sector stakeholder organisations as well as the public and businesses is essential to ensure that responsibility for flood risk management is shared beyond RMAs and that individuals and businesses know what actions to take to minimise their own risk and manage the impacts should events occur. The Environment Agency conducts annual market research surveys with people that they know live in areas at risk of flooding in England.

The results from the 2020/21 flood survey (EA, 2021a) are below:

- Approximately half of those surveyed believe the area where they live is at risk of flooding, but fewer (around 4 in 10) think that their property is at risk.
- Perception of risk is lower among 18–34 year olds and those in rented accommodation. Although 70% have undertaken some flood prevention action overall, young people and renters are less likely to take action.
- Just under a fifth have received advice/support in the last year but this was lower among young people and renters.

These results are very similar to the most recent published findings from 2013/14 (Langley and Silman, 2014).

Research commissioned to support the CCRA regarding the impact of behaviour on climate risks identified the key importance of education and awareness-raising regarding levels of risk and

information on the effectiveness of adaptation measures. This could help overcome the misconception that adaptation only includes structural or property adjustments which may be deterring greater action. Case study respondents also highlighted that they would be more likely to undertake personal protective measures if they received financial support from the government or private sector. Respondents from one case study also stated that they would be more willing to take action if there was evidence of government taking climate impacts seriously, for example with less or better designed floodplain development (Power *et al.*, 2020).

Research has also highlighted how social factors, heuristics (mental shortcuts or ‘rule of thumb’) and choice overload affect willingness to act (EA, 2020a). Further research is required to facilitate behaviour change as part of flood risk management.

#### 5.4.2.1.2.4 Emergency planning and response

Community resilience involves working with local people and businesses to assess, plan for emergencies and act to manage flooding. In England and Wales, Local Resilience Forums (LRFs) develop emergency plans and provide information on what to do before, during and after a flood at the local level, which should support recovery from flood events. Other bodies (such as the Environment Agency/NRW, National Flood Forum, local councils, utility companies, Highways England) also provide advice on how to prepare for and recover from flooding events. There is little data to assess the effectiveness of the work of LRFs in emergency responses when floods occur. However, analysis of emergency responder (ambulance and fire services) times under various flooding scenarios identifies how even low magnitude floods can lead to a reduction in mandatory response times, which is particularly marked in large cities (Yu *et al.*, 2020). This is explored further in Risk H12: Risk to Health and Social Care Delivery.

The Defra Flood Resilience Community Pathfinder scheme from 2012-2015 was set up to enable and stimulate local people and businesses at high risk of flooding to work with key partners to develop innovative local solutions (Twigger-Ross *et al.*, 2015). Key findings from this work include evidence that social resilience and community capital can be enhanced through improving the accessibility of information and knowledge of flood risk and roles and responsibilities. Economic resilience was enhanced through support to SMEs in particular and institutional resilience has been achieved through the establishment of over 100 flood groups across England.

Flood warnings in England (and Wales), are provided through the joint Met Office/Environment Agency Flood Forecasting Centre. The Cabinet Office ResilienceDirect platform also provides street-level surface water flood forecasts to authorities and Category 1 and 2 responders (Cabinet Office, 2018). In January 2019 the response to the Multi Agency Flood Plan Review was published (Defra and EA, 2018). The Review identified that existing emergency planning processes and arrangements were effective in responding to small and medium sized flood events, but the response to major events affecting multiple local authorities and thousands of people, such as the winter 2015/16 floods, needed improvement. It also resulted in updated guidance for developing multi-agency flood plans better reflecting the needs of LRFs, acknowledging technological developments such as ResilienceDirect, and providing a more consistent framework for developing Multi-Agency Flood

Plans enabling ease of transfer across LRFs, and including provision for the Environment Agency to conduct three year health-checks on the plans (Defra, 2020d).

There are also measures in place to support local authorities, communities and businesses when major flood events occur. MHCLG activates the emergency Bellwin scheme on the first day of flooding (Sandford, 2019). Under Bellwin, local authorities dealing with the flooding can apply to have 100% of their eligible costs, above a threshold, reimbursed by the government. This could be for items including rest centres, temporary accommodation and staff overtime.

The Flood Recovery Framework sets out a core package of business and community recovery support, which is made available by Ministers when severe weather has significant impacts across multiple authorities (DCLG, 2017). The package comprises several schemes that are deployed to local authorities to help communities and small and medium businesses return to normality.

#### 5.4.2.1.3 Northern Ireland

##### 5.4.2.1.3.1 Planning policy

Northern Ireland's latest Strategic Planning Policy Statement was published in September 2015 (Department of the Environment, 2015) and contains requirements on climate change adaptation and mitigation. The main adaptation provisions include avoiding development in flood risk areas, retaining and restoring natural floodplains and promoting integrated flood risk management. DfI Planning and local Council Planning Authorities are advised by DfI Rivers, who are the custodians of flood mapping, flood risk management and suitability of land for development. Climate change is a factor that is taken into consideration in the provision of that advice.

The use of SuDS in new developments is promoted as the preferred approach under 'Planning and Flood Risk' within the Strategic Planning Policy Statement for Northern Ireland (SPPS). The Regional Development Strategy 2035 (RDS) also proposes that SuDS should be encouraged as part of significant development proposals. In particular, it is proposed that *'all new urban stormwater drainage systems should incorporate measures to manage the flow of waters which exceed design standards (exceedance flows) in order to help protect vulnerable areas'* (DRD, 2012). Local Authority Local Development Plans (LDPs) are required to take account of the RDS and to conform to the SPPS, both of which encourage the use of SuDS for new developments. However, this has not translated into widespread uptake of SuDS. Local authorities, such as Belfast City Council, are working to address the gap between the policy aspirations and take-up on the ground.

##### 5.4.2.1.3.2 Flood risk management policy and investment

Northern Ireland legislation to enact the European Floods Directive was introduced in 2009 via The Water Environment (Floods Directive) Regulations (Northern Ireland) 2009 (Department for Infrastructure, 2020b). The legislation requires the following elements of the 2<sup>nd</sup> cycle to be completed by the following dates:

- Northern Ireland Flood Risk Assessment – December 2018 (published) (Department for Infrastructure, 2018).
- Review of flood risk and flood hazard maps for Areas of Potential Significant Flood Risk – December 2019 (published).
- Flood Risk Management Plan – December 2021. The plan will set out objectives and measures for managing the risk of flooding (under development).

Flood Risk Management Plans (FRMPs) were produced under the 1<sup>st</sup> cycle for each of Northern Ireland's three principal river basin districts (North Eastern, Neagh Bann and North Western) in 2015 (Department for Infrastructure, 2015). The Plans highlight the flood hazards and risks in the 20 most Significant Flood Risk Areas in Northern Ireland from flooding from rivers, the sea, surface water and reservoirs, and set out a framework in which measures to manage flood risk will be delivered or planned for at a local level over the next six years. The aim of the Plans is to manage the adverse consequences that flooding could have on human health, the environment, cultural heritage and economic activity. The Plans focus on the '3 Ps' in relation to managing aspects of flood risk: prevention, protection and preparedness. They also set out how relevant authorities will work together and with communities to reduce flood risk.

A draft Flood Risk Management Plan (FRMP) for the period 2021–2027, aimed at managing and mitigating the risk of flooding in Northern Ireland, has been published for a six-month public consultation (December 2020 until June 2021); the FRMP will be finalised by December 2021 (Department for Infrastructure, 2020a). The Plan focuses on 12 APSFR identified in the 2<sup>nd</sup> cycle NI Flood Risk Assessment (Department for Infrastructure, 2018). In addition, nine 'Transitional Areas of Potential Significant Flood Risk' (TAPSFR), previously identified as APSFR in the 2011 PFRA, have been determined to ensure continuity between 1<sup>st</sup> and 2<sup>nd</sup> cycle FRMPs and to facilitate implementation of any outstanding measure commitments from the 1<sup>st</sup> cycle FRMPs.

The Department for Infrastructure in Northern Ireland is primarily responsible for arterial drainage and flood protection and implementation of the Water Environment (Floods Directive) Regulations (NI) 2009. In 2013–14, some £6 million was spent on flood defence schemes (Priestley, 2017). Total capital expenditure on flood and coastal erosion risk management in 2015/16 was £24.7m, an almost 20% increase since 2010/11 (£20.7m) (NIAO, 2016). Social vulnerability is not specifically included as a parameter in assessing prioritisation in relation to DfI Rivers Flood Alleviation / Flood Risk Management schemes although health impacts have been monetised in NIFRA 2018.

#### 5.4.2.1.3.3 Flood risk management interventions

The Homeowner Flood Protection Grant Scheme in Northern Ireland is a government funded flood grant scheme which entitles homeowners to get 90% funding of flood protection measures up to a value of £10,000. The additional 10% of the cost and any extra cost above £10,000 must be funded by the homeowner themselves. The grant is not means tested and all successful applicants have to contribute 10% of the cost of the works. Eligible properties will have to have been flooded in the past or are located in a known flood area. Any properties that were initially granted planning approval from 1<sup>st</sup> January 2009 are ineligible. In addition to this, any homes owned by the Housing Executive, any registered housing association or other third party are also ineligible from the flood



grant. Finally, any properties that are likely to benefit from a government backed flood alleviation scheme in the next five years will also be ineligible. A review of this grant scheme is currently underway.

#### 5.4.2.1.3.4 Emergency planning and response

In Northern Ireland there are three Emergency Preparedness Groups that comprise multi-agency partnerships. These have dedicated working groups to manage natural hazards such as flooding (Executive Office, 2011). The Met Office and its partners provide the UK Coastal Monitoring and Forecasting Service (UKCMF) for the DfI Rivers in Northern Ireland (Met Office and EA, 2020). In Northern Ireland, DfI NI has a key role in the provision of a fast and effective flood emergency response with a view to mitigating any threat to life or property and responding where possible to requests for assistance from the public whose property has suffered or is threatened by flooding. DfI also discharges Lead Government Department (LGD) responsibilities for the co-ordination of flooding emergencies. While the response to and recovery from an emergency will require many organisations, each delivering their own responsibilities and functions, the role of the LGD is a key one as it provides detailed and specific flood risk expertise that assists the wider overall multi-agency response to flooding. The Civil Contingency structures in Northern Ireland provide an effective mechanism to deliver co-ordinated emergency flood response with the Civil Contingencies Group (Northern Ireland) (CCG (NI)), providing strategic leadership. There are three regional level multi-agency Emergency Preparedness Groups (EPGs), with the purpose of ensuring an appropriate level of preparedness to enable effective multi-agency response to emergencies which have a significant impact on the public. Flooding and severe weather working groups are established for matters specific to flood risk management, and these groups facilitate the preparation of emergency plans which provide a structure for government preparation, response and recovery from flooding or other severe weather events. Exercises are carried out to test the plans and debriefs are held to identify improvements in the preparedness, response and recovery phases.

In Northern Ireland, the Regional Community Resilience Group (RCRG) was established in 2013 to help local communities prepare for and respond to weather related emergencies. The RCRG develops a consistent approach to community engagement to help individuals and communities to be better prepared and more self-reliant during emergencies. The group includes partners from government departments, local government, emergency responders, utility providers and the voluntary sector, and works on this multi-agency basis to facilitate adequate planning and preparation for community response and recovery, to cope with emergency incidents in 'at-risk' communities.

In addition to helping local communities to develop community emergency plans, resilience groups are advised of relevant weather information and provided with alert information, where available, and resources so that they can make appropriate preparations to 'self-help' for incidents that may affect property, the highway network and their community. The group is currently working with over 30 communities across Northern Ireland to provide an additional layer of support for those communities at risk from severe weather.

#### 5.4.2.1.4 Scotland

##### 5.4.2.1.4.1 Planning policy

The Town and Country Planning (Development Management Procedure) (Scotland) Regulations 2013 state that planning authorities must, before determining an application for planning permission, consult with SEPA where the development is likely to result in a material increase in the number of buildings at risk of being damaged by flooding (SEPA, 2017). Scottish Planning Policy (SPP) (Scottish Government, 2014b) includes a section on Managing Flood Risk and Drainage highlighting the Third National Planning Framework (NPF)'s support for a catchment-scale approach to sustainable flood risk management (Scottish Government, 2014a). The SPP promotes a precautionary approach to flood risk from all sources, taking account of the predicted effects of climate change; flood avoidance and flood reduction. The policy highlights the importance of the planning system preventing development in areas at flood risk or where flood risk could be increased elsewhere.

The NPF and SPP are currently under review. A Position Statement on the fourth NPF was published in November 2020, highlighting the need for a fresh approach and significant investment in infrastructure to address climate change (Scottish Government, 2020a). Specific issues that need to be addressed to achieve this ambition are identified as (i) reducing communities' exposure to flooding by future-proofing the design of the built environment and investing in natural infrastructure; (ii) promoting natural flood risk management and strengthening policies on the water environment and drainage infrastructure; (iii) restricting development in flood risk areas; (iv) adapting existing infrastructure where climate change may increase vulnerability to flooding; and (v) placing greater importance on flood risk management and coastal protection, as the interface between planning on land and at sea is important.

A study was published in 2016 to assess the effectiveness of Scotland's local planning authorities in implementing national planning policy in both planning for flood risk and the effects of climate change, and ensuring new development is avoided in areas at risk of flooding (LUC, 2016). This identified that whilst awareness of climate change in general across local authorities was very good, understanding of the likely tangible effect on the risks posed by flooding was poor. Policies were also generally weaker in terms of translating the avoidance principle (not developing in areas at flood risk), which is afforded additional significance in the context of climate change. Spatial strategies showed little evidence of having been influenced by the outcomes of flood risk assessment, with almost no clear consideration of climate change. Land allocations were particularly problematic, with proposals frequently at significant risk of flooding even before the effects of climate change were taken into account. 12 out of 16 plans had allocations with outstanding flood risk objections (usually from SEPA) dealt with at Examination.

Under the Water Environment (Controlled Activities) (Scotland) Regulations 2011, it is a general requirement for SuDS to be installed where new developments produce surface water that drains into the water environment in order to protect water quality. Where legally required, SuDS should also manage surface water drainage up to a 1 in 30-year rainfall event and protect water quality. Not all SuDS are required to manage surface water flooding. Surface water drainage in Scotland falls

under water company and road authority responsibility for sewers and roads respectively, while surface water flooding falls under the flood authorities.

#### 5.4.2.1.4.2 Flood risk management policy and investment

The Flood Risk Management (Scotland) Act 2009 created a general duty for Scottish Ministers, the Scottish Environment Protection Agency (SEPA) and responsible authorities to exercise their functions with a view to reducing overall flood risk. Responsible authorities include local authorities, Scottish Water and other public bodies designated by Scottish Ministers (Priestley, 2017). The second edition of statutory guidance to SEPA, local authorities and Scottish Water on fulfilling their responsibilities under the Flood Risk Management (Scotland) Act 2009 was issued by the Scottish Government in 2019 (Environment and Forestry Directorate, 2019). The changes the Government wishes to bring about are set out in the following six long term key outcomes: (i) a reduction in the number of people, homes and property at risk of flooding; (ii) rural and urban landscapes with space to store water and slow down the progress of floods; (iii) coasts and estuaries managed in a way which aims to reduce flood risk; (iv) sustainable surface water management that decreases burdens on sewer systems, whilst also delivering reduced flood risk and an improved water environment; (v) a well-informed public; and (vi) flood management actions undertaken that are effective in the long-term and adaptable to future climate change.

SEPA is producing a new national Flood Risk Management Strategy, which will help to steer and focus its statutory role and responsibilities for flooding, and embed adaptation as a key principle to ensure flood risk management plans and actions tackle future flood risk. The Strategy aims to support individual and community resilience to flooding and take forward flood risk management, involving a wide range of powerful partnerships working to increase Scotland's flood resilience now and in the future. It is intended that the Strategy will be published in 2021, dependent on COVID-19 implications and other associated capacity issues.

The latest Scottish Programme for Government (PfG) states that Scottish Government will invest an additional £150 million for flood risk management over a five-year period from 2021/22, as well as continuing to provide £42 million per year to local authorities (Scottish Government, 2020c). The Scottish Flood Forum received a grant of up to £193,000 from the Scottish Government in 2020-21. Scotland takes deprived communities into account in its prioritisation matrix used to rank schemes. Within its six outcomes for flood risk management, two specifically focus on vulnerability: FR4 considers social vulnerability and FR6 is concerned with vulnerable receptors.

Flood Risk Management Strategies have been developed for each of the 14 Local Plan Districts in Scotland (SEPA, 2015). They are approved by Scottish Government and published by SEPA as Scotland's strategic flood risk management authority. These strategies have been produced in collaboration with all 32 local authorities, Scottish Water and other organisations with a responsibility or interest in managing flooding. The strategies are supplemented by local flood risk management plans, which set out detailed actions and how these will be delivered by local authorities and their partners.

#### 5.4.2.1.4.3 Flood risk management interventions

The Scottish Government's PfG commits to reviewing the approach to Blue-Green Cities and bringing forward proposals to deliver this by the end of 2020, and taking action to progress climate adaptation including Scottish Water pursuing further partnerships to create natural blue-green infrastructure. A policy document 'Water Resilient Places – A Policy Framework for Surface Water Management and Blue-Green Infrastructure' was published early in 2021. This aims to improve the management of surface water flooding by complementing and supporting existing policy and organisational responsibilities as set out in the Flood Risk Management (Scotland) Act 2009. The policy objectives aim to make surface water management relevant to all sectors and make it a core consideration in designing for climate adaptation, sustainable placemaking and delivering great blue-green places to live.

In addition, Forestry and Land Scotland's climate emergency commitments are working to ensure that, as storms, floods and droughts become more common, their "forests and land are part of the solution and not part of the problem" (Forestry and Land Scotland, 2021). Scotland has a NFM network and currently there are just under 100 NFM actions identified in Scotland's Local Flood Risk Management Plans.

Scotland's Living with Flooding Action Plan is starting to prepare for the transition from Flood Re with insurance companies and Flood Re involved with the Property Flood Resilience Delivery Group (Scottish Government, 2019b).

A commitment to address PFR was included in the 2018 PfG. The Property Flood Resilience Delivery Group (PFRDG) brings together a range of stakeholders to work together to ensure that Scotland is better prepared for flood events. The PFRDG developed the Living with Flooding Action Plan in 2019 to help raise awareness of the benefits of PFR and encourage property owners, the construction and insurance industries and the general public to implement PFR measures (Scottish Government, 2019b). Research commissioned by ClimateXChange, on behalf of the Scottish Government and the PFRDG (Pettit and Kerr, 2020), found that take up in Scotland was low, (estimated to be 1,400-1,500 properties). It also found that approximately 81,000 properties could benefit from some flood resilience measures. A second research project is currently investigating the barriers to take up and will make recommendations for actions to increase uptake. This will feed into the PFRDG's review of the Living with Flooding Action Plan in 2021.

#### 5.4.2.1.4.4 Emergency planning and response

Multi-agency co-ordination in Scotland, for the management of emergencies such as flood incidents, is undertaken through three Regional Resilience Partnerships (RRPs - North, East and West) which are disaggregated into 12 Local Resilience Partnerships (LRPs).

With support from the Scottish Government, the Scottish Flood Forecasting Service (SFFS) brings together SEPA's expertise in flood warnings and Met Office expertise in weather forecasting to provide accurate flood forecasts for key responders (Met Office and SEPA, 2020). The Met Office

also provides the UK Coastal Monitoring and Forecasting Service (UKCMF) for SEPA (Met Office and EA, 2020).

#### 5.4.2.1.5 Wales

##### 5.4.2.1.5.1 Planning policy

In September 2020 the Welsh Government asked Senedd Cymru (the Welsh Parliament) to scrutinise the draft National Development Framework (Welsh Government, 2019e). This sets a strategy for addressing key national priorities through the planning system, including sustaining and developing a vibrant economy, decarbonisation, developing resilient ecosystems and improving the health and well-being of communities across Wales. The review highlighted the importance of the planning system in ensuring development is not at risk of flooding and the importance of natural solutions to manage flood risk. The draft National Development Framework was finalised in 2021 to become the Future Wales: National Plan 2040 (Welsh Government, 2021c).

National planning policy regarding planning flood risk in Wales is set out in Technical Advice Note (TAN) 15: Development and Flood Risk (Welsh Assembly Government, 2004). This guidance was published in 2004 and an updated draft was published for consultation in 2019 (Welsh Government, 2019c). The revised TAN15 is due for publication in 2021 and will incorporate the previous TAN14 (coastal erosion), with the revised guidance providing a greater focus on climate change. The review includes an updated guidance document and a new Flood Map for Planning, to replace the existing Development Advice Map. As elsewhere, development in Wales can be permitted in Flood Zone 3 subject to acceptability tests/flood free thresholds.

In Wales, inclusion of a SuDS is a mandatory condition to secure planning permission under the Flood and Water Management Act (2010) Schedule 3; this requirement has been in place since 7 January 2019 (Welsh Government, 2019h). SuDS must be designed and built in accordance with Statutory SuDS Standards published by the Welsh Ministers and SuDS Schemes must be approved by the local authority acting in its SuDS Approving Body (SAB) role, before construction work begins (Welsh Government, 2018b).

##### 5.4.2.1.5.2 Flood risk management policy and investment

The new National Strategy for Flood and Coastal Erosion Risk Management in Wales (Welsh Government, 2020c) clarifies roles and responsibilities around FCERM, and is developed around the following objectives: (i) improving understanding and communication of risk, preparedness and building resilience; (ii) prioritising investment to the most at risk communities, preventing more people becoming exposed to risk; and (iii) providing an effective and sustained response to events. This sets the overall policy framework for Local Flood Management Strategies delivered through Natural Resources Wales and local authorities. The strategy highlights the importance of building resilience to climate change including through adaptive approaches and stresses the importance of understanding climate change projections to improve understanding around risk. It is the first National Strategy to incorporate Welsh legislation on the environment, wellbeing and sustainable drainage.

Between 2016 and 2021, the Welsh Government invested £390 million into helping manage flood risk, reducing risk to more than 45,000 properties across Wales. Following flooding in 2020, the Welsh Government provided over £4.4m to repair flood defences (Welsh Government, 2020d). Recent changes to funding include full support for preparing and designing new flood schemes, raising grant rates for the construction of coastal defences to 85%, and the introduction of a new £2m natural flood management programme (Welsh Government, 2020d). The determination of investment for flooding is influenced by NRW's Communities at Risk Register which uses outputs from flood models to consider the number of people at risk, the hazard they are exposed to over a range of probabilities, the speed of onset of flooding and their ability to respond in terms of social vulnerability to flooding. It also uses factors such as availability and standard of flood warnings and flood defences.

#### 5.4.2.1.5.3 Flood risk management interventions

The Welsh Government, NRW and partners across Wales strongly support and promote the use of NFM across Wales as detailed in the new national strategy (Welsh Government, 2020c). In 2020, the Welsh Government awarded £2 million to NFM projects across Wales intended to help Risk Management Authorities – such as local authorities and NRW combat the impacts of climate change as flood risks intensify, using natural methods. As part of the NFM programme, RMAs will work together on monitoring outcomes and sharing best practice to improve understanding of what works well in different environments, which should help encourage greater take up of NFM in future (Welsh Government, 2020b).

The new national strategy supports the use of PFR in Wales and a code of practice to standardise the UK provision of PFR. Welsh local authorities can also access the Environment Agency's supplier framework for PFR but there is currently no national scheme to implement PFR.

#### 5.4.2.1.5.4 Emergency planning and response

Flood warnings in England and Wales are provided through the joint Met Office/Environment Agency Flood Forecasting Centre. A number of different organisations are involved in coordinating flood response and recovery; including the RMAs who lead the response to flooding from different sources, but local flood authorities and infrastructure agencies also have a role alongside NRW. In very severe situations (such as following Storm Dennis), the Emergency Coordination Centre Wales (ECCW) is convened. Response and recovery work has included:

- Supporting communities and partners through the challenges posed by these significant flood events.
- Assessing and repairing damage to flood assets and land assets on the Welsh Government woodland estate that NRW manage.
- Responding to large numbers of requests for information.
- Understanding the immediate equipment replacement or enhancement needs, including to ICT systems and services.

#### 5.4.2.1.6 Flood insurance UK-wide

The UK Government introduced the UK-wide Flood Re re-insurance scheme in 2016, working with the insurance industry to support access to insurance for households at high flood risk for whom premiums might otherwise be unaffordable. In 2019/20, Flood Re provided cover for over 196,000 household policies. Since its introduction, Flood Re has reported that 96% of households that had previously flooded could access flood insurance quotes from five or more insurers whereas before the scheme only 9% could get quotes from two or more insurers. Four out of five households were reported to have seen more than a 50% reduction in their insurance premium (Flood Re, 2018). Recent research commissioned by Defra identified that 88% of households in high flood risk areas (83% in 2015) have a policy which covers both buildings and contents insurance whilst 6% have separate policies for contents and buildings insurance (Defra, 2018a). However, this was lower for those living in rented properties, with 34% stating that they did not have a contents insurance policy, which had declined from 41% in 2015.

Flood Re's second Transition Plan in 2018 (Flood Re, 2018) envisions a market with affordable, risk-reflective household insurance. A review for flood insurance cover following flooding in South Yorkshire found the vast majority of owner occupiers had building and contents insurance but tenants were less well protected (Blanc, 2020). At least 6% of owner occupiers and 11% of tenants had insurance which excluded cover for flooding but there was no evidence that any of the affected properties were ineligible for Flood Re. The review states that *'If replicated across the country, this could mean tens of thousands of vulnerable households who are unnecessarily unprotected against flooding and missing out on the support that has been set up to help them.'*

Flood Re was established to promote the availability and affordability of household insurance for eligible homes and, over its lifetime, enable a transition to affordable risk-reflective pricing for household insurance for those at risk of flooding. The QQR was conducted in 2019 to identify how to make Flood Re more efficient, responsive and flexible, and also to recommend any changes required to enable and accelerate the transition process (Flood Re, 2019). Key recommendations include working with insurers to 'build back better' homes after a flood enabling the payment of claims to include an additional amount for resilient or resistant repair and rewarding householders who proactively install flood resilience measures with discounted premiums on their home insurance policies. These recommendations should further support increased take up of PFR.

The Government estimated that Storms Desmond and Eva led to almost 16,000 residential properties being flooded, but the ABI reported only 9,700 residential insurance claims, suggesting low levels of cover could be a factor, particularly in Carlisle, where there were fewer claims than expected (EA, 2018b). Local reports also suggest problems of insufficient insurance in Cumbria, in part relating to previous flood experiences, which affected premiums and excesses for residents (Cumbria Community Foundation, 2018), but also reluctance to make claims, due to fears that properties would become uninsurable or that claims could result in high premiums and make trying to sell property difficult. They suggest many flood victims did not inform their insurance companies and some did not apply for resilience grants to which they may have been entitled (Cumbria County Council, 2018), indicating ongoing questions about how best to address insurance gaps. Clear progress is being made in facilitating the transition from Flood Re to risk-reflective, affordable home insurance.

#### 5.4.2.2 Adaptation Shortfall (H3)

Current flood risk to people is already assessed as high magnitude across the UK, hence we consider here whether there is an explicit goal of ‘no increase in risk’, if future actions will manage the risk back down to present day levels in the face of climate change, whether lock-in is being adequately managed, and whether recent climate trends are well accounted for in policy (see Chapter 2: Watkiss and Betts, 2021; Table2.7).

**Accounting for recent and future trends in climate.** Whilst policy is accounting for recent climate trends and future climate projections in England, Scotland and Wales, further action is required in Northern Ireland which does not have a national strategy to manage flood risk.

**Managing the risk down to present-day levels in the future and avoiding lock-in.** In relation to these criteria, our assessment is that further action is required across all UK nations. Specifically, none of the policies as yet have quantified evidence to show that actions will keep the risks at today’s level in the future as the level of hazard from flooding increases. Even in the enhanced adaptation scenario (Sayers *et al.*, 2020a), increases in flood risk are seen for many of the metrics considered, suggesting that either further innovation beyond current flood risk management measures is needed, or an explicit goal for managing flood risk, that allows for residual risk to increase in the future, is required across the UK. This sort of explicit goal, which could involve consideration of the relocation of some communities, is not currently featured in UK flood policies.

Our assessment suggests there are also some evidence gaps or questions about implementation of policy, identified below.

- **Lock-in from new development.** Housing development continues to occur on the flood plain e.g. in England (the latest data suggests that this accounts for 9% of all new development in England (MHCLG, 2020)) and in Scotland. Research conducted in 2016 regarding the effectiveness of Scotland’s local planning authorities in implementing national planning policy suggested that the outcomes of flood risk assessment and climate change were not sufficiently influencing spatial strategies (LUC, 2016), which could lead to inappropriate development. Whilst climate resilient homes can be built on the flood plain, either with community level defences in place or with PFR measures, further evidence regarding the degree to which resilient measures are being incorporated is required and whether these homes are resilient to future changes in flood risk.
- **Uptake of green sustainable urban drainage.** There is insufficient evidence regarding the implementation of SuDS, and particularly green SuDS, as this is not monitored (e.g. CCC (2019a)).
- **Flood insurance.** Across the UK, while Flood Re is providing support to increase access to affordable insurance for households at high risk of flooding who seek support, there are still many households that do not have insurance, or have insurance that does not include flood cover. While flood insurance can play a protective role and a safety net in the event of a



flood, household take-up rates vary by income and tenure, and some groups are less well protected.

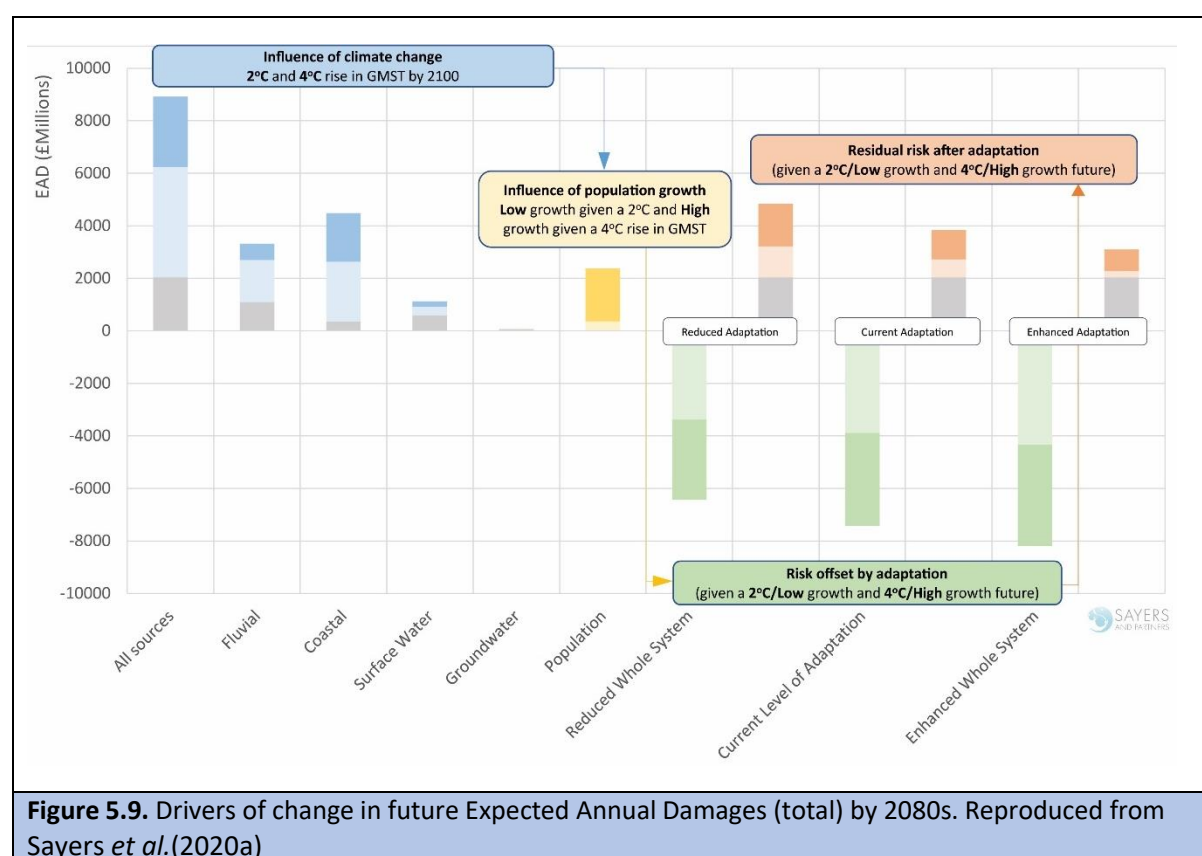
- **PFR.** The rate of PFR installation is almost certainly well below the optimum, which is certainly the case in England (CCC, 2019b), and there are a lack of incentives across the UK to increase take up of property level flood resilience measures where these are an appropriate household response. Some well-known barriers include lack of motivation from householders, lack of familiarity and access to information, costs and behavioural biases to taking action, and lack of professional skills and knowledge (CCC, 2019a). The new FCERM Policy Statement commits to encouraging a faster transition of the market place for PFR, providing more advice, products and incentives to enable this transition.
- **Responsibilities and accountability.** There is a public expectation that risk will be managed by the UK Government, devolved administrations and national environmental regulation agencies, as well as other public bodies such as local authorities (e.g. Power *et al.* (2020)). This may hinder individuals and communities' own involvement in taking steps to improve their preparedness. Governments and other national agencies across the UK are keen to enhance greater individual and organisational responsibility by setting out expectations and roles and responsibilities for managing flood risk now and in the future. This area is likely to remain a continued challenge requiring continual awareness raising and knowledge sharing. Behavioural science insights should inform future measures to encourage a greater sharing of responsibility.
- **Inequalities.** Disadvantaged communities in urban and rural areas remain at proportionally high risk of flooding now and in the future, although flood risks to health affect all populations, not just low income households (Sayers *et al.*, 2017a). This situation is projected to continue into the future despite current Government investment regimes in England, Scotland and Wales prioritising deprived communities. Greater attention needs to be given to integrating policy objectives and delivery across agendas including preferentially selecting interventions to reduce flood risk and response measures that do not disadvantage certain population groups.
- **Maintenance budgets.** Further investment in maintenance is required to ensure that flood risk management measures can continue to manage current risk and have the potential to manage future risk. This has been particularly highlighted for England with the Efra Committee's flood report highlighting the need for a long-term resource budget settlement, aligned with the increased capital investment, so that the Environment Agency and other RMAs can plan for and maintain new and existing flood and coastal defences (Efra, 2021).

## 5.4.2.3 Adaptation Scores (H3)

Table 5.15. Adaptation scores for risks to people, communities and buildings from flooding			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially	Partially	Partially	Partially
(High confidence)	(Medium confidence)	(High confidence)	(High confidence)

## 5.4.3 Benefits of further adaptation action in the next five years (H3)

The types of adaptation measures required and the impacts on managing flood risk vary spatially. Figure 5.9 shows how the increase in risk is more sensitive to the adaptation choice than others. This highlights the limited opportunities for enhanced adaptation in some of the small local authorities and those in coastal settings with limited available land outside of the flood plain for new development. The difference between the alternative adaptation portfolios is also particularly marked for some local authorities, suggesting that enhanced adaptation efforts in these areas will be required to manage future risk. Importantly even with enhanced adaptation, residual risk is not inconsequential, requiring sustained action to minimise the impacts of this risk and potentially requiring transformational solutions such as relocation.



Whilst Defra's Policy Statement, the English and Welsh national FCERM strategies and the proposed strategy for Scotland promote many elements of the enhanced whole system adaptation scenario, the challenge now is to move from strategic aspirations to delivery on the ground. Specific areas where our assessment suggests additional action is needed in the next five years are summarised below:

- The shift from protection to embracing a range of measures that achieve resilience is supported across the UK. Articulating and promoting exactly what this means in practice is likely to be challenging. Whilst there is a substantial body of research being conducted to inform and facilitate this change in approach, working across the UK nations and widely sharing outcomes from case study examples and initiatives such as the Flood and Coastal Resilience Innovation programme in England is needed to enable a more integrated approach. This could also generate fuller public engagement about the respective roles of different actors in reducing risk and taking adaptive measures, as well as help to promote community level responses that could build resilience.
- There is an economic case for increasing investment in socially vulnerable areas, and whilst current funding approaches prioritise support for deprived communities in England, Scotland and Wales, introducing new metrics focused on reducing social vulnerability to flooding in UK government and devolved administration outcome measures could help further mitigate the social costs of flooding, which could improve upon current approaches (Sayers *et al.*, 2017b).
- It would be beneficial to understand how new developments built in at-risk areas are being made safe and resilient, for all new properties in high risk locations. This information should be publicly available by development, and should include whether properties are being protected by flood defences (and if so to what level) as well as the extent to which PFR has been implemented in new development.
- The lack of a statutory requirement for SuDS across the UK, other than Wales, and lack of monitoring in all jurisdictions remains a continued challenge. With surface water flood risk projected to increase under all scenarios and the need to achieve biodiversity (and soon environmental) net gain in all new developments, there is a strong argument for greater enforcement.
- Data collected for England shows that the uptake of PFR measures remains much lower than the potential cost-beneficial rate of uptake (CCC, 2019b), and there is a lack of data on uptake in the devolved administrations. Understanding of the barriers to PFR uptake has improved, informed by research in England and Scotland; subsequent recommendations now need to be acted upon.

#### 5.4 3.1 Indicative costs and benefits of additional adaptation (H3)

The three portfolios in the research report on future flood projections influence the future increase in risk to properties and associated EAD (Sayers *et al.*, 2020a). In a scenario of 4°C global warming in 2100 with high population growth, continuing Current Levels of Adaptation is expected to offset

future EAD in the 2080s by around £7.4 billion (all damages, not just residential, direct and indirect). Under the same scenario, an Enhanced Whole System is estimated to offset £8.2 billion EAD but only £6.4 billion is offset by the Reduced Whole System, meaning that the net increase in risk is much greater at around £2.8 billion. It is important to note that residual risk remains under all scenarios as it is not realistic to eliminate all flood risk. As detailed earlier, national strategies in place (or in train) aspire to many of the elements of the Enhanced Whole System, the degree to which these are effectively implemented will determine the level of flood risk reduction.

There is a very large literature on the costs and benefits of flood protection for adaptation, indeed, it is the most comprehensively covered area in the literature (OECD, 2019). These studies tend to find high benefit to cost ratios, for both hard and soft protection measures, and for grey and green infrastructure. However, values are highly site- and context-specific.

In terms of property resilience and resistance measures, there have been several studies that have investigated the costs and benefits of these measures. These include Defra (2008), EA (2015a) and Royal Haskoning DHV (2012; 2019). The most recent report from the CCC (Wood Plc, 2019) found that a number of flood resilience and resistance measures could be considered no-regret adaptation measures (i.e. a benefit to cost ratio of greater than one in cases where there is a greater than 1% chance of Annual Exceedance Probability (AEP)). In general, this literature reports that all measures are more expensive if retrofitted rather than installed in new builds. For resistance measures, the difference between costs of retrofitting vs. incorporating into new builds are more modest. However, the applicability of each of these measures depends on the type of flooding (recurrence and depth), as this alters the relative cost-effectiveness (and benefit to cost ratio).

Given the residual damage costs even with current flood management policy, this is clearly an area where there are benefits of future action, and in many cases these benefits will outweigh the costs.

#### 5.4.3.2 Overall Urgency Scores (H3)

<b>Table 5.16. Urgency scores for Risks to people, communities and buildings from flooding (H3)</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	High	High	High	High

While there has been a significant enhancement of the policy framework across all four UK countries since CCRA2 was published, an adaptation shortfall remains under a current planned adaptation scenario (and even the enhanced scenario as set out in Sayers *et al.* (2020a). There is a lack of evidence that implementation of the latest plans will cancel out any additional future risk from climate change in order to maintain the risk at today's levels (the criteria as set out in Chapter 2 (Watkiss and Betts, 2021) for risks that are already high magnitude), that lock-in is being fully managed, or that the whole range of current and future risk has been accounted for. Therefore,

although there is evidence of positive progress, all countries have been given a “More Action Needed” urgency score.

#### 5.4.4 Looking ahead (H3)

This is already an area where adaptive management (and adaptation pathways) are being developed and this provides a clearer link to an iterative approach that could link successive CCRA2s (and NAPs).

Further information is required with regards to the following:

- National assessment and action regarding the scale of current and future residual risk and the degree to which this can be addressed by measures such as increased take up of PFR, or whether more transformational actions such as the relocation of communities is required.
- Scale of adoption of SuDS and their effectiveness across the UK.
- Impacts of the new Partnership Funding formula in England.
- Benefits and challenges of natural flood management (NFM) across the UK.
- Carbon neutral flood defences and their contribution to the Net Zero emissions goal.
- Impacts of new national strategies, particularly in relation to promoting and achieving resilience.
- More support and agency (independent decision-making capacity) provided to communities to manage their own risk and reduce reliance on government action, although this is likely to require some public sector funding support.

### 5.5 Risks to the viability of coastal communities from sea level rise (H4)

Sea level rise is likely to threaten the long term viability of some coastal communities in the UK. Some small communities in the south and east coasts of England and the west coast of Wales already face risks to their viability as a result of coastal change due to the current and/or future impacts of coastal flooding and/or erosion. The UKCP18 projections, which were published after CCRA2, suggest faster sea level rise than identified in UKCP09 projections for similar scenarios. Understanding of coastal risk has been enhanced through a greater focus on its assessment, particularly in Scotland via its national coastal change assessment – Dynamic Coast. In addition, national policy and strategy development in England, Scotland and Wales has given coastal change a higher profile. Whilst the threats to the viability of coastal communities are widely recognised and Shoreline Management Plans (SMPs) include (non-statutory) policies to support managed realignment, there is little evidence at the national scale of a long-term strategy that is assessing coastal community viability or planning action to support communities facing this uncertain future. Risks to the viability of coastal communities from sea level rise was identified as a risk in 2017 (CCRA2) and there have been developments in terms of evidence, adaptation policy and action. A range of public and private sectors reports and research have been published that look at risks globally and across the UK as well as new policy and practice at national and local levels.

This risk is focused on coastal change (physical change to the shoreline caused by coastal erosion, coastal landslip, permanent inundation or coastal accretion) that is of such severity that the long term sustainability and viability of coastal communities is threatened. Whilst coastal flooding is

covered under Risk H3, it is also considered in this risk with regards to the potential for catastrophic flooding, driven by changes in sea level and storminess that can threaten the viability of coastal communities. Coastal change can be defined more narrowly as only relating to coastal erosion; it is important to be aware that in CCRA3, this risk is investigating the impacts of the wider definition of coastal change (driven by sea level rise) for people, communities and buildings. Similarly, we apply a broad definition of coastal communities meaning those living/working in or visiting coastal locations. Viability relates to the future physical existence of a settlement, for example its potential loss from coastal erosion, the future ability for people to live and work in a settlement (which may be affected by safety issues related to flood risk), and economic viability, wherein the risk of coastal change affects the local economy to such a degree that is no longer viable to invest in the area.

There are several emerging issues for this risk:

- The increased realisation that it is unrealistic (i.e. prohibitively expensive with major safety implications) to promote a ‘hold the line’ policy for all of the coastline. This raises the fundamental questions of how to: (i) plan our future shoreline on the open coast and along estuaries; and (ii) deliver practical portfolios of adaptation options that are technically feasible, balance costs and benefits, can attract appropriate finance, and are socially acceptable.
- The increased realisation that there are barriers to implementing the policy of ‘managed realignment’ or ‘no active intervention’ in SMPs. For example, many historical coastal landfill sites for waste are located in low-lying coastal areas that need to be protected, but SMPs may promote Managed Realignment or Active Intervention (Brand, 2017; Beaven *et al.*, 2018).
- The use of adaptation pathways to manage coastal flood risks that take account of future uncertainties. The adaptive pathways approach developed for the Thames Estuary 2100 project has gained recognition but has not yet been applied more widely (Haigh and Nicholls, 2019) (See Section 2.3 in Chapter 2: Watkiss and Betts, 2021).
- The importance of early community and wider stakeholder engagement where the future viability of communities may be threatened.

### 5.5.1 Current and future level of risk (H4)

#### 5.5.1.1 Current Risk (H4)

##### 5.5.1.1.1 Current risk – UK wide

CCRA2 highlighted that globally, the coastal zone is one of the most vulnerable areas to current and future climate change, whilst also being one of the most valuable to people for economic, social, cultural and health reasons. Coastal erosion and flooding have been reshaping the UK coastline since the last ice age, but sea level rise has been notable over the last 50 years. It is important to note that sea level rise does not operate in isolation; it is the combination of sea level rise with storminess and

coastal processes such as sediment movement and erosion that creates a risk of such magnitude that it can threaten the long term sustainability of whole communities.

Since CCRA2, there have been repeated concerns world-wide highlighting the risk of rising sea levels on the world's coasts and increasing evidence regarding the risks that climate change poses to our coastal zones. In the UK, millions of people live in low-lying coastal areas that are vulnerable to coastal flooding and erosion, and protection remains essential to reduce risk (CCC, 2018). Consistent data is not collected across the UK on the number of properties lost to, or at risk of coastal erosion, therefore the estimates provided may be based on different methodologies.

Insurance or compensation is not currently available to mitigate against the risk of losing properties. While building surveys conducted by mortgage companies will report on erosion risk, cash buyers could complete a property transaction without knowing if a property they are purchasing on the coast is at risk of erosion (CCC, 2018).

Coastal floods are amongst the most dangerous natural hazards and are one of the most significant risks that the UK faces, as identified in the most recent National Risk Register (HM Government, 2020b). Coastal flooding results from extreme sea levels which arise as a combination of four main factors: waves, astronomical tides, storm surges and relative mean sea level. Tidal lock can also occur when the level of the incoming high tide stops river water flowing out to sea, meaning rivers cannot discharge flood waters.

SurgeWatch is a database of coastal flood events in the UK from 1915 to 2016 which documents and assesses the consequences of historical coastal flood events around the UK (Haigh *et al.*, 2017). Each flood event is ranked using a multi-level categorisation from 1 (nuisance) to 6 (disaster) (based on levels of inundation, transport disruption, costs and fatalities). 329 events (a period of high sea levels and/or waves arising from a distinct storm, which were associated with coastal flooding) were identified from the start of 1915 to the end of 2016.

Category 5 events are those that involve either loss of life or reliable evidence that defences and/or flood warnings, and a substantial institutional response to the event, prevented multiple fatalities. Category 6 events (Disaster) are reserved for large consequence events that are associated with multiple fatalities due to drowning. Direct flood-related fatalities are linked to only six UK floods since 1915. Of the 329 events in the database, 18 were identified as Category 4, eight Category 5, and only the January/February 1953 event was ranked Category 6. The eight category 5 floods are shown in Table 5.17 below. These, and the 18 Category 4 floods, are in various locations along the England, Scotland and Wales coastlines, but England's east coast has seen the most catastrophic events in 1953 and 2013.

The frequency with which extreme high-water levels are exceeded has increased over the last 150 years, driven primarily by the observed rise in relative mean sea level. Furthermore, saltmarshes, shingle and sand dunes, which provide important buffering against floods, are in decline. Population growth, changes in land use and enhanced asset values in floodplain areas have also increased exposure to coastal flooding. However, overall, the frequency and consequences of flooding have

reduced over time due to improvements in flood defences, together with advances in flood forecasting, warning and emergency response and spatial planning (Haigh *et al.*, 2020).

**Table 5.17.** Historical severe coastal flooding events in the UK. Source: (Haigh *et al.*, 2017)

Date	Category	Locations affected	County, region or country
January 1953	6	Norfolk, Kent, Spurn Head, Humber, London	North Sea (England), Thames
October 1927	5	Mersey, Fleetwood, Blackpool, Sandylands, Cardigan Bay, Criccieth, Aberglaslyn, Porthmadog (Portmadoc)	Mersey, Fleetwood, Blackpool, Sandylands, Cardigan Bay, Criccieth, Aberglaslyn, Porthmadog (Portmadoc)
January 1928	5	London (City), Southwark, Putney, Hammersmith, Westminster, Mersea, Maldon (Essex), Norfolk, Stranraer	London (City), Southwark, Putney, Hammersmith, Westminster, Mersea, Maldon (Essex), Norfolk, Stranraer
November 1977	5	Fleetwood, Morecambe, Pilling, Blackpool, Lytham	Irish Sea (England)
January 1978	5	Grampian coastline, Wells-next-the-Sea, King's Lynn, Cleethorpes, Wisbech, Sandilands, Mablethorpe, Trusthorpe, Ingoldmells, Walcott, Deal, Alnmouth, Amble Harbour, Berwick-upon-Tweed, Blyth, Hayling, Cowes, Bembridge	North Sea (England, Scotland), English Channel (the Solent)
December 1981	5	Somerset (Burnham on Sea, Brean, Weston, Uphill, Sand Bay, Wick St Lawrence, Kingston Seamoore, Clevedon, Pawlett), Portsmouth, Hayling Island, Langstone, Fareham, Ryde, Cowes, Freshwater, Yarmouth, Southampton	English Channel (the Solent), Bristol Channel
February 1990	5	Pensarn to Kinmel Bay, Towyn, Rhyl, Ffynnonogroyw, Prestatyn, Clwyd	Irish Sea (Wales)
January 2005	5	South Uist, Barra (Scotland), Warkworth (River Coquet, Northumberland)	Atlantic (North West Scotland); North Sea (North East)
December 2013	5	Sunderland, Hull, Boston, Great Yarmouth, Lowestoft, North Berwick, Jaywick, Blackpool, Cleveleys, Walcott, Cromer, Whitstable, Portgordon, New Brighton, Rhyl, Havant, Cowes, Southampton	North Sea (England, Scotland), English Channel (Kent to the Solent), Irish Sea (North Wales, England, Scotland), Atlantic Scotland

#### 5.5.1.1.2 Current risk - England

In England, 8,900 properties are currently at risk from erosion if coastal defences are not taken into account. Environment Agency analysis of the national coastal erosion risk map (EA, 2018c) shows that about 1,800 km of England's coastline (total coastline is 4,500 km in length) is at risk of erosion. Defra has highlighted that since 1996 around 50 permanent properties and 30 temporary properties



have been lost as a result of coastal erosion, plus 100 or so beach huts (Ballard *et al.*, 2018). Caravans would also have been lost had they not been moved back from the cliff edge.

The severe consequences of coastal flooding are illustrated by the large spatial ‘footprint’ of the winter 2013/14 floods (simultaneous flooding along extended coastline stretches during the same storm) and the temporal ‘clustering’ of the flood events (events occurring one after another in close succession) (Dissanayake *et al.*, 2015; Haigh *et al.*, 2020). The spatial extent of events can greatly influence the magnitude of inundation (Lewis *et al.*, 2011). The winter flood of 2013/14 included the 5-6 December 2013 storm, during which water levels exceeded the severe storm of 1953 on the east coast. However, whilst impacts occurred (including the flooding of 803 properties in Boston, Lincolnshire), the number of people and properties protected by flood defences meant these impacts were far less than in 1953 when 307 people died (Haigh *et al.*, 2020).

With regards to the viability of specific communities, North Norfolk is at risk of coastal erosion with villages along the coast between Cromer and Great Yarmouth particularly at risk. The second-generation SMPs for this coastline (adopted in 2010 and 2012) advocated changes in policy from continued defence to No Active Intervention meaning that in the long-term properties, local communities, environmental assets and infrastructure are at risk of loss. Recent events in the area include the evacuation of residents by the local authority from 13 properties close to eroding cliffs in Hemsby, Great Yarmouth in March 2018 and the demolition of five properties, with seven further properties were demolished in May 2018. In December 2013, three houses and a lifeboat hut in Hemsby, Norfolk were also swept into sea along with a popular cafe at Caister-on-Sea (Ballard *et al.*, 2018).

Similarly, parts of the Essex coast (Tendring) and East/West Sussex and Dorset are already identified as being at risk of coastal change which could affect the viability of communities in the future (Royal Haskoning DHV, 2019).

The magnitude score for the current risk is low, reflecting that hundreds of people are directly affected and less than £10m annual damage is likely.

#### 5.5.1.1.3 Current risk - Northern Ireland (H4)

19.5% of the coastline in Northern Ireland is currently at risk of coastal erosion (McKibbin, 2016). Approximately 5,675 people or 2,720 households are at risk of coastal flooding in Northern Ireland (McKibbin, 2016). No evidence has been identified in relation to communities in Northern Ireland whose current viability is threatened by coastal change, and therefore the current magnitude score is low.

#### 5.5.1.1.4 Current risk – Scotland

Nearly a fifth of Scotland’s coastline (3,802 km – 19%) is at risk of erosion within the next 30 years, threatening some of the country’s most prized land and infrastructure. Between a half and a third of all coastal buildings, roads, rail and water networks lie in these erodible sections. 865 km of the soft (erodible) coastline has moved since the 1970s – 11% (423 km) has advanced (accreted), 12% (442

km) has retreated (eroded), and the remaining 77% (2,936 km) has remained approximately stable. Compared with the historical period (1890 to 1970 and adjusted for time period), the proportion of advancing coast has fallen by 22%, since 1970, whilst the proportion of retreating coast has increased by 39%. Larger shifts in the balance of erosion and accretion are found particularly on the east coast and Solway Firth (Scottish Government, 2017b). Since the 1970s, average erosion rates have doubled to 1 metre per year, compared with the historical baseline of 0.5 metre per year (Hansom *et al.*, 2017). These observed changes since the 1970s are consistent with expectations of climate change (Scottish Government, 2017b).

No evidence has been identified regarding coastal communities in Scotland whose current viability is threatened by coastal change, and therefore the current magnitude score is low.

#### 5.5.1.1.5 Current risk – Wales

In Wales, 400 properties are identified as being at current risk of coastal erosion (Welsh Government, 2019d). The December 2013 storm surge event led to estimated temporary repair costs of £80,000 in North Wales, 90% of which occurred within Conwy County Borough Council. Permanent restoration costs were estimated at over £6.9million, of which over 70% occurred within Conwy County Borough Council and over 25% within Denbighshire County Council (NRW, 2014a).

Currently, the Gwynned coast in West Wales is at risk of coastal flooding with Fairbourne being the first community in the UK whose long term viability has been recognised as unsustainable in policy terms (Royal Haskoning DHV, 2021). Porthmadog and Pwllheli are also at risk but not to the same level of severity, at least in the near term. In addition, the long term stability of the shingle bank protecting the village of Newgale in Pembrokeshire has implications for its long term viability (Atkins, 2018a). Whilst it is known that Fairbourne's future viability is threatened by sea level rise, on an immediate basis the threat is identified as 'low magnitude' with hundreds of people at risk and the potential for less than £1m annual damage (see Chapter 2, Watkiss and Betts, 2021, for quantitative definitions of risk magnitude used in CCRA3).

#### 5.5.1.2 Future risk (H4)

##### 5.5.1.2.1 Future risk - UK-wide

Global mean sea level rise will cause the frequency of extreme sea level events at most locations to increase. Local high-water levels that historically occurred once per century (historical centennial events) are projected to occur at least annually at most locations by 2100 under all Representative Concentration Pathway (RCP) scenarios (High confidence) (IPCC, 2019). The increasing frequency of high-water levels can have severe impacts in many locations depending on the level of exposure (High confidence) (IPCC, 2019).

For the UK average, total sea level rise is slightly lower than for global mean values across all scenarios. However, the UKCP18 sea level projections (Palmer *et al.*, 2018) are consistently larger than in the previous UKCP09 projections for similar emissions scenarios (Defra, 2009). This is because the more recent projections include ice dynamics from the Antarctic ice sheet (Palmer *et*

*al.*, 2018). The pattern of sea level rise across the UK can be broadly characterised by a north-south gradient, with larger sea level rise to the south and London, where between 0.53 m and 1.15 m of sea level rise is projected by 2100 relative to 1981–2000 levels, with projections partly consistent with the upper part of the range of the CCRA3 scenario of 4°C global warming by 2100<sup>6</sup> under a high-emissions scenario is projected. Sea level rise of over 1 m by 2100 is also projected around the Scottish coast for certain scenarios, with significant risks in low-lying islands particularly in the Western Isles (Garner *et al.*, 2018; EA, 2019a; Bamber *et al.*, 2019)

The Met Office has generated exploratory time-mean sea level projections that extend to 2300 (EA, 2019a). These projections are inherently uncertain due to the long time horizon; it is possible that higher values could result, potentially associated with accelerated ice mass loss from West Antarctica. For London and Cardiff, the projection ranges at 2300 are approximately 0.5–2.2 m, 0.8–2.6 m and 1.4–4.3 m for projections driven by the extended scenarios with the RCP2.6, RCP4.5 and RCP8.5 concentration pathways, respectively. The values for Edinburgh and Belfast are substantially lower, with corresponding ranges at 2300 of approximately 0.0–1.7 m, 0.2–2.1 m and 0.7–3.6 m, illustrating the geographic variations around the UK. While the upper estimates of sea level rise are greater than H++ values for the 21<sup>st</sup> century, they occur much later and are subject to lower confidence given the extended time horizons (Palmer *et al.*, 2018). By 2300, sea water levels with a current probability of only 1 in 10,000 years (0.01%), could be experienced every year. There are also additional low-likelihood high-impact scenarios that have been identified by recent global expert elicitations (Garner *et al.*, 2018; Bamber *et al.*, 2019), which raise the possibility of even higher increases under high-emission scenarios, with conceivably 2 m increases by 2100.

In summary, the upper range for the latest UK sea-level rise projections is higher than previous estimates, implying increased risk of coastal change. The likelihood of compound effects from tidal flooding and extreme rainfall is increasing, which can greatly exacerbate flood impacts (MCCIP, 2020). Future sea level rise will increase the coastal flood and erosion risk and increase exposure (particularly infrastructure) in coastal zones (Tables 5.10) (CCC, 2018). This is explored further in Chapter 4 (Jaroszowski, Wood and Chapman, 2021).

#### 5.5.1.2.2 Future risk - England

Across England, the number of residential properties at risk of coastal erosion are estimated to increase from between 3,500 and 5,500 today to between 58,000 and 82,000 by 2100 (Table 5.18; CCC, 2018).

CCRA2 highlighted that future sea level rise of less than 1 m is likely to be a major contributor to welfare losses; sea level rise of 0.5–1 m could lead to 200 km or more of coastal defences becoming particularly vulnerable to failure in some conditions and may not be cost-effective to maintain in the future. This is around 4% of the English coastline and 20% of the coastline with coastal defences (Sayers, *et al.*, 2015).

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<sup>6</sup> UKCP18 marine projections driven by CMIP5 climate models with the RCP8.5 concentration pathway. Note that the multi-model mean projects global warming of 4.3°C in 2081–2100 so is within the range consistent with CCRA3 higher scenario – see Chapter 2: Watkiss and Betts, 2021

**Table 5.18.** Residential properties in England at current and future risk of coastal erosion.

	Present day		Mid-Century		End-Century	
	Mid-estimate	High-estimate	Mid-estimate	High-estimate	Mid-estimate	High-estimate
No. residential properties	3,535	5,489	21,600	31,800	58,000 (67,500)	82,100 (167,700)
The numbers in brackets represent estimates where the erosion of complex cliffs has been included in the assessment. Source: CCC (2018).						

Risk H3 sets out projected future coastal flooding risk for the Reduced Whole System adaptation scenario (do minimum). This highlights significant increases in the population at risk of coastal flooding for England. With high population increase and a scenario of 4°C global warming in 2100, the number of people at significant risk of coastal flooding (1 in 75-years or 1.3% Annual Exceedance Probability (AEP)) is projected to increase from just over 100,000 now to 757,000 by the 2080s. This substantial increase could have implications for communities that are already at severe risk, particularly along the east coast.

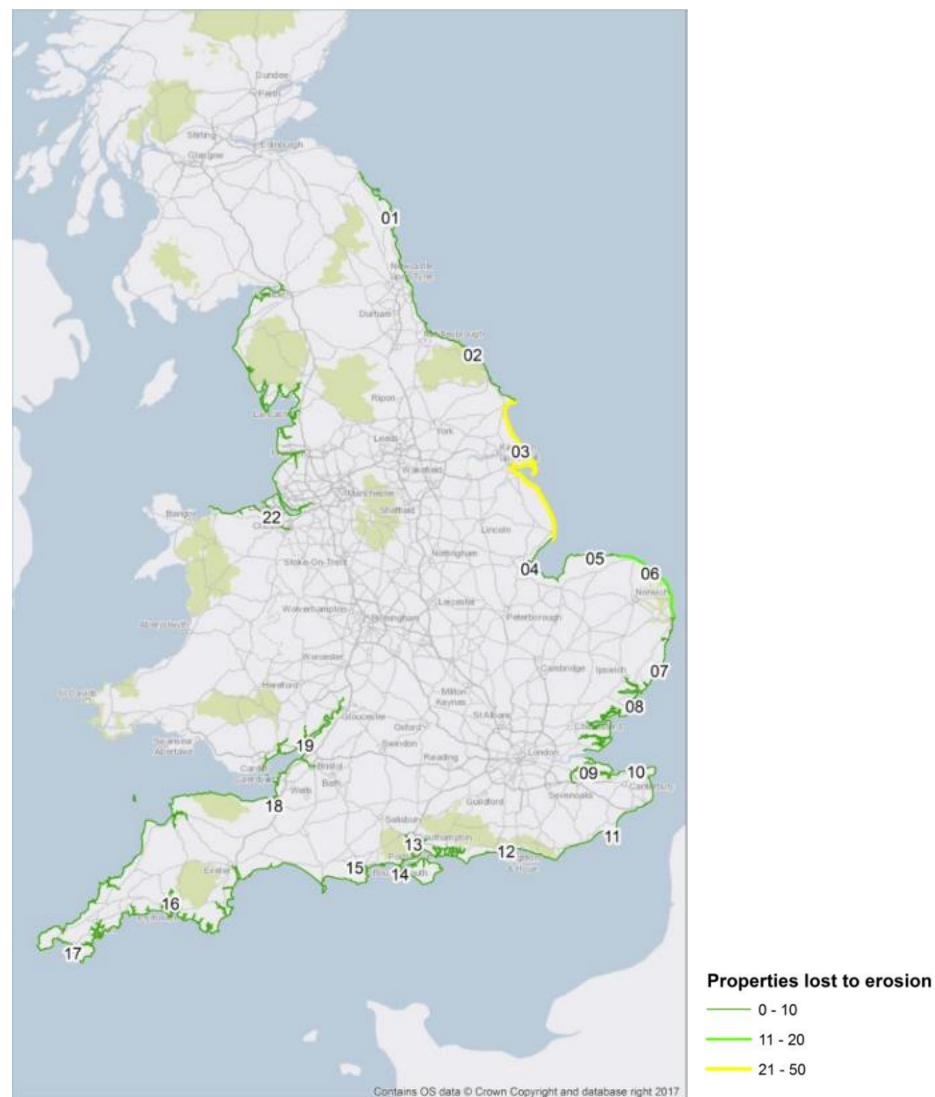
Defra conducted a mapping exercise of properties at risk of coastal erosion over the next 20 years using existing national datasets and assuming the interventions set out in SMPs are fully implemented across all epochs (Figure 5.10). The mapping does not include caravans which are numerous on all stretches of the coast in close proximity to the cliff edge, and which are likely to be at considerable risk (Ballard *et al.*, 2018).

The areas identified under the current risk section will be at more threat with regards to their viability in the future due to climate change impacts, specifically sea level rise, and therefore the magnitude rises to medium and then high for the 2050s and 2080s with both +2°C and +4°C in 2100 climate futures. However, there is low confidence associated with this due to the uncertainty associated with communities reaching the tipping point where viability is threatened.

#### 5.5.1.2.3 Future risk - Northern Ireland (H4)

Risk H3 sets out projected future coastal flooding risk in terms of the number of people likely to be affected and potential EAD for the Reduced Whole System adaptation scenario (no additional adaptation) [Figure 5.5. and Figure 5.6 in Risk H3]. This highlights significant increases in population at risk of coastal flooding for Northern Ireland. With high population increase and 4°C global warming in 2100, Northern Ireland's risk is projected to increase by 550% by the 2080s from a baseline of 500 to almost 3,200.

50% of the coastline of Northern Ireland has a high likelihood of functional change by 2100 and over the next century, over 400 m of the dune system at Murlough could be lost (Low confidence) (Cooper and Jackson, 2018).



**Figure 5.10.** National Mapping of Coastal Erosion risks (Short Term) – England. Legend corresponds to properties at risk under Shoreline Management Plan (SMP) policy in next 20 years. The numbers refer to SMPs: <https://www.gov.uk/government/publications/shoreline-management-plans-smpls/shoreline-management-plans-smpls> Reproduced from Ballard *et al.*, 2018

With the increase in potential risk, the magnitude score is low for the 2050s and medium for the 2080s but with low confidence as further research is required to fully understand the level of coastal change risk in Northern Ireland.

#### 5.5.1.2.4 Future risk – Scotland (H4)

In Scotland (and Wales), for continuation of the Current Level of Adaptation scenario for low population increase and a 2°C climate future, coastal flooding risk decreases, showing the impact of minimal adaptation. With the Reduced Whole System scenario, high population increase and 4°C global warming in 2100, significant risk of coastal flooding is projected to increase by just 10% from a baseline of almost 13,500 people to 14,800 by the 2080s.

If recent erosion rates were to continue in the future then by 2050 at least 50 residential and non-residential buildings, 1.6 km of railway, 5.2 km of road and 2.4 km of clean water network as well as significant areas of runways, and cultural and natural heritage sites are expected to be affected by coastal erosion (Scottish Government, 2017a). If erosion rates increase in the future, as expected with climate change, Dynamic Coast 1 (National Coastal Change Assessment) and the National Flood Risk Assessment are likely to underestimate the extent of assets at risk from future coastal erosion and associated coastal flooding. Dynamic Coast 2 will be published in 2021 and will consider how sea level will rise with further increasing erosion rates. This will update anticipated erosion mapping considering tidal mapping updates and methodological improvements to incorporate the anticipated effects of relative sea level rise. The anticipated erosion mapping can be compared with SEPA's indicative flood mapping, to better improve awareness of erosion enhanced flooding within Flood Risk Management Strategies. The updated mapping can also be compared with the locations of assets, e.g. infrastructure and buildings, to better inform risk assessments.

Large numbers of assets are sited close to potentially erodible coasts (including 30,000 buildings, 1,300 km of roads and 100 km of railway lines) and therefore could be affected (Scottish Government, 2017b). The future implications for infrastructure will have implications for communities if basic services such as power, water and ICT are affected as well as affecting access to employment, education, health and leisure facilities.

The future magnitude score for Scotland increases from low to medium by the 2050s and 2080s under both climate futures; this particularly relates to the projected increase in coastal erosion.

#### 5.5.1.2.5 Future risk – Wales

In Wales, coastal flood risk is projected to decrease with a scenario of Continued Level of Adaptation, low population, and 2°C global warming by 2100. With the Reduced Whole System scenario, high population increase and 4°C global warming by 2100, the risk in Wales is projected to increase by 260% from a baseline of just over 10,000.

In Wales, 2,126 properties are estimated to be at risk from coastal erosion within a century if defences are not maintained (based on 2014 data) (Dodds, 2017).

As communities in Wales are already identified as being at risk, with their long-term viability threatened by sea level rise, the future magnitude score increases from low to medium and then high for both climate futures.

#### 5.5.1.3 Lock-in and thresholds (H4)

Coastal change is the ultimate lock-in as it represents the total loss of land and property. For some areas such as Fairbourne in West Wales, the East Anglia coast, Tendring and the Thames Estuary in England, the 2050s have been identified as a crucial time period for adaptation. A range of lock-in issues related to managing coastal change risks is summarised below:

- Development in coastal areas that are at risk of erosion or flooding.
- Installation of defences that affect areas further along the coast.

- Irreversible decisions, such as implementation of the decision to no longer Hold the Line in SMPs (i.e. defences not put in place) leading to irreversible change (land-use).
- Insufficient engagement of local communities, stakeholders, policymakers and decision-makers to ensure full appreciation of the severity of the issues now, leading to making it more difficult to address in the future.

Due to the challenges of protection, some communities may not be viable places to live in the future. If these areas are not identified, development could continue in these areas, leading to stranded assets. Already, there is an increased emphasis on engagement with communities to enhance resilience and this will continue. Consideration for moving whole communities or infrastructure is slowly starting to happen now but the realisation of how to achieve this is weak and fragmented (CCC, 2018). Community relocation is also challenging when the risks are not immediate and uncertain (see Fairbourne case study).

Land use planning has a clear role to play in preventing lock in-by ensuring that development is not permitted in areas at risk of major coastal flooding and coastal erosion where protection is unlikely to be sustainable. In addition, bold steps are required to identify communities that may not be sustainable in the long term and discuss management or relocation options due to climate risks. Plans need to be put in place, as early as possible, to start transitioning development away from areas that cannot be protected without unacceptable residual risk or unacceptable cost and moved towards sections of the coast that have lower risks – these areas should be safeguarded for future development in local plans.

The consideration of thresholds and their use in adaptation pathway approaches are well established for coastal protection (Haasnoot *et al.*, 2013). These consider different management or policy responses for a series of thresholds associated with increasing levels of future sea level rise. In the UK, such an approach was used in the Thames Estuary 2100 Plan (Ranger *et al.*, 2013). Specific thresholds have also been identified at locations such as Fairbourne, Norfolk, Suffolk and Essex (Tendring) coasts. The risks of exceeding these thresholds varies significantly between 2°C and 4°C pathways.

#### 5.5.1.4 Cross-cutting risks and inter-dependencies (H4)

Interacting risks have the potential to increase the risk of coastal change in three different ways – the interaction of climate hazards, impacts of other sectors affecting people and the built environment and the interaction between climate hazards and social policy. The following impacts have been identified:

##### 5.5.1.4.1 Interaction of climate hazards

- Combined sources of flooding - the combined effect of coastal and surface flooding results in significant impacts for the built environment. In addition, high river and tidal levels can also create local surface water flooding as surface water may not be able to drain away (WSP, 2020).

- Sea level rise and wave-tide interactions is a cumulative risk rather than an interdependency. Assessments do not always consider the combination of sea-level rise with wave-tide interactions. In modelling the Irish Sea, Lewis *et al.* (2019) found that a combined assessment (with a sea-level rise of between 0.44 m and 2 m) could result in a 5% increase in the high-water wave height in some areas. Hence, overall flood risk (if defences were accounted for), could increase, which may have local implications for flood risk management strategies.
- The combination of high river and tidal levels resulting in flooding will be exacerbated by sea level rise leading to increased impacts in the future.
- For barrier island coasts (e.g. Blakeney Point, Norfolk), continued erosion (e.g. through a policy of no active intervention) could see shorelines continue to roll landwards, thus increasing mainland erosion hotspots. (See Risk [N17], Chapter 3: Berry and Brown, 2021).

#### 5.5.1.4.1 Interaction between the risks from climate change and social policy

- Government policy on regeneration of coastal towns – investment and regeneration remain important but need to be in alignment with interventions to manage coastal change. The Welsh Coastal Risk Management Programme introduced in 2016 aims to achieve coastal risk management plus wider economic growth and regeneration benefits.
- Local authorities ‘creating’ beaches to support tourism and the impact of increased nourishment on natural processes.
- Owners of industrial assets on the coast (such as oil refineries, gas processing plants and chemical plants) implementing adaptations to sea level rise may have wider impacts for local communities.
- Designated environmental and heritage sites along the coast and the drive to protect these where public funding for such interventions is not possible due to the focus on numbers of people affected in public funding allocation formulae.

Whilst tourism in coastal areas may increase as a result of warmer summers, there are likely to be detrimental impacts for marine and coastal habitats that could affect tourism and recreation, particularly where beaches are affected by either erosion or accretion (MCCIP, 2020). In addition, visitor pressures can affect natural habitats including those, such as dunes, that help mitigate the impacts of coastal change. For example, the draft Sefton Coast Plan in North West England refers to an Adaptation and Sand Dune Management Plan and highlights the need to reduce the impact of visitors by directing them to less vulnerable areas to increase coastal resilience (Lymbery *et al.*, 2016). Achieving a balance between supporting a thriving visitor economy and protecting natural habitats for both climate resilience and biodiversity reasons is essential and for those local authorities where this is an issue, visitor management strategies are required to comply with the requirements of the Habitats Regulations and enhance the resilience of the coast to climate change.

#### 5.5.1.5 Implications of Net Zero (H4)

Coastal defences often involve extensive structural engineering with embodied implications in terms of its manufacture. Risk H3 provides further details on the Environment Agency’s Carbon Planning Tool, which enables the assessment of carbon over the whole life of built assets, and also refers to



developments and requirements in Scotland and Wales. There is no evidence of a similar requirement in Northern Ireland.

Air travel may reduce as a result of the UK's Net Zero commitment (as well as the implications already seen from the COVID-19 pandemic, detailed below) which could increase UK 'staycations' and increase visitors to coastal resorts. Increased visitor numbers – which could also happen through population growth – would support local economies including their ability to fund/contribute to resilience measures, but also could have impacts for adaptation in terms of visitor pressure affecting dunes and other natural systems that provide natural defences, as well as the need to ensure the safety of visitors, for example by ensuring that caravans are not located too close to areas of known coastal change.

#### 5.5.1.6 Inequalities

Coastal change has particularly severe impacts for vulnerable communities due to the intrinsic deprivation that exists in many coastal communities, particularly in England and Wales. The economic and social deprivation seen in many English and Welsh coastal communities following the decline of domestic tourism in the second half of the 20<sup>th</sup> century has been the topic of numerous reports and inquiries and acknowledged by successive governments. Despite a multitude of regeneration schemes to address deprivation in English coastal communities, disadvantage has persisted and when considering a range of economic and social indicators (such as economic output, earnings and employment) many seaside towns continue to fall below the national average (House of Lords, 2019). The 2019 Index of Multiple Deprivation (ONS, 2019) identifies the most deprived neighbourhood in England as being to the east of the Jaywick area of Clacton-on-Sea. This neighbourhood was also identified as the most deprived in the 2015 and 2010 indices. Six Blackpool districts also featured in the top 10 most deprived neighbourhoods in 2019. Jaywick and Blackpool are also identified as being at high risk of coastal flooding.

The report also highlighted that social deprivation puts greater financial burdens on local authority resources, with people who require new accommodation as a result of coastal erosion often being dependent on the availability of council housing. Isolated rural communities tend to be more dependent on their immediate supporting community infrastructure (e.g. transport and communications links, jobs, local shops and social activities) which may also be threatened by erosion. It also highlighted the socio-economic vulnerability of many people in coastal areas, with high proportions of older residents and transient populations, low employment rates and high seasonality of work, physical isolation and poor transport links. Furthermore, the report identified a lack of understanding in disadvantaged coastal communities of the range of possible climate change impacts they potentially face and how to respond appropriately, together with their lack of agency and capacity to take action. Concern was also highlighted regarding affluent property owners, including businesses, with more agency and capacity to engage and influence, attempting to obtain planning permission for private defences to coastal erosion that may not always be of environmental benefit.

Research into flood disadvantage in Scotland conducted in 2015 revealed that Falkirk, West Dunbartonshire, Highland and Dumfries and Galloway have the highest number of extremely/acutely

flood-disadvantaged data zones in relation to coastal flooding with over 28,000 people potentially flood-disadvantaged. The report identified that coastal areas (up to 2 km from the coast) have a higher proportion of extremely and acutely vulnerable and disadvantaged data zones than areas located further inland. Therefore, coastal areas should be considered as a priority for flood risk management actions in order to reduce the impacts on vulnerable communities (Scottish Government, 2015b).

The Welsh Government has developed a coastal community typology based on their socio-economic characteristics to aid coastal planners and other users understand which particular planning developments and policy initiatives may be appropriate in particular areas (Welsh Government, 2016).

Coastal areas are not homogenous and in many areas around the UK coastline, relatively affluent populations live in expensive coastal properties. Defra's recent scoping study (Ballard *et al.*, 2018) concerning adaptation to coastal change highlighted areas at most risk of coastal erosion which ranged from low income rural and often isolated communities in the East Riding of Yorkshire and Scarborough to coastal locations in Norfolk and across the South and South West of England, with a mix of both wealthy villages/individual properties and deprived, low income communities.

Understanding the local context is essential in developing adaptation strategies and interventions. Recent research highlights that recent investment has been relatively effective in addressing flood risk exposure inequality and social deprivation in the 20% most deprived areas in England (EA, 2020f). However, deprived coastal communities still experience significant inequalities for high and medium likelihood of flooding, and these inequalities are more pronounced than in inland areas. In addition, rural inequalities are higher than those identified in urban areas.

#### 5.5.1.7 Immediate observations regarding the impacts of COVID-19

The immediate effects of COVID-19 and associated lockdown requirements will have more of a socio-economic than coastal change threat to coastal communities. The economies of many local areas are dominated by seasonal tourism, and the restrictions on movement during spring/summer 2020 will have reduced visitor numbers (both domestic and international) significantly, with an associated detrimental impact on local revenue and employment. However, the medium-term impacts of increasing staycations mean that coastal areas are likely to benefit from increased domestic visitors.

In addition, local authorities are having to focus their efforts on emergency planning regarding the virus, leaving less resources available for coastal risk management. Obtaining contributions to match Government funding for coastal risk management schemes is also likely to become more challenging as both public and private sector organisations will have far less resources available.

#### 5.5.1.8 Magnitude Scores

Magnitude is low now, rising to high in all climate futures for England and Wales due to current risk and projections for sea level rise. It is assessed as low for Scotland and Northern Ireland, now and

medium in the future. Current magnitude scores are high confidence for all countries other than Northern Ireland, related to the evidence available as set out above. Confidence for all countries and both climate futures is low for the 2080s due to the uncertainty associated with climate projections over the longer term.

**Table 5.19.** Magnitude score risks to the viability of coastal communities from sea level rise

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Low  (High confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)	High  (Low confidence)	High (Low confidence)
<b>Northern Ireland</b>	Low  (Medium confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium (Low confidence)
<b>Scotland</b>	Low  (High confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)	Medium  (Low confidence)	Medium (Low confidence)
<b>Wales</b>	Low  (High confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)	High  (Low confidence)	High (Low confidence)

## 5.5.2 Extent to which current adaptation will manage the risk (H4)

### 5.5.2.1 Effects of current and adaptation policy and commitments on current and future risks (H4)

#### 5.5.2.1.1 England

Coastal flood management is driven by integrated engineering, planning, insurance and preparedness activities. In recent years, there has been an increasing emphasis on community or individual led activities to increase resilience to coastal flooding and erosion. The role of Partnership Funding (Defra, 2011a) in England has opened up the extent that central government funds can help adaptation.

In England, a new Policy Statement (HM Government, 2020a) and accompanying Flood and Coastal Erosion Risk Management (FCERM) Strategy (EA, 2020e) were published in 2020. The Strategy has a strategic objective 1.3 to help coastal communities transition and adapt to climate change, and notes *“for some coastal locations it will unfortunately no longer be technically, socially or*

*economically feasible to continue to provide protection from flooding and coastal change. In these places, the focus of resilience both now and in the future, will be on keeping people safe from harm and to develop resilience actions that minimise the impacts of flooding and coastal change on communities".* It places an action on RMAs to facilitate this transition. It also states that looking forward to 2100, people in every place need to be able to identify the decisions for managing flooding and coastal change that need to be taken now and those that can be made in the future. The strategy also makes reference to the need for greater uptake of adaptive pathways approaches to ensure the country remains resilient to a range of future change. The Policy Statement commits to review the effectiveness of existing planning policy on Coastal Management Areas, the current mechanisms and legal powers Coastal Protection Authorities can use to manage the coast, and the availability and role of financial products or services that can help people or businesses to achieve a managed transition away from areas at very high risk of coastal erosion.

In England (and Wales – see section below), Shoreline Management Plans (SMPs) provide non-statutory guidance on how to manage the coast in different areas (policy units), through four options of hold the line, advance the line, managed realignment or no active intervention (Defra, 2011b).

SMPs are applied through three epochs over a 100-year period. Where a policy change is expected to occur and significant adjustment will be required (e.g. from a present policy of hold the line to managed realignment), Coastal Change Management Areas (Royal Haskoning DHV, 2019) have been formed to help formalise this process, including better integrated planning, new developments and learning to ensure a smooth transition. SMPs are non-statutory but are intended to inform wider strategic planning. An SMP Refresh was initiated in 2019 focusing on changes since the second round of SMPs were published, such as new legislation, planning guidance and climate projections, and advising how these should be taken into account in SMPs. It does not involve developing a new set of SMPs (Coastal Group Network, 2019). Informed by the Environment Agency's current refresh of technical evidence supporting Shoreline Management Plans Defra's Policy Statement on Flooding and Coastal Erosion commits to a review of national policy for SMPs to ensure local plans are transparent, continuously review outcomes and enable local authorities to make robust decisions for their areas.

The planning system has an important role to play in preventing development that could be at risk from coastal flood risk and coastal change. The National Planning Policy Framework (MHCLG, 2019a) requires the consideration of flood risk over the lifetime of development, which for residential development is typically 100 years. An example of where increased flood risk due to climate and coastal change was scrutinised was at a 2019 Public Inquiry in Essex, which considered the issue of whether single storey chalets should be allowed to be occupied during the winter months when coastal flood risk is highest (Sherratt, 2019). The Planning Inspector supported the Council's stance that winter occupation should not be permitted on the basis of flood risk over the lifetime that those developments could be occupied. Whilst currently defended against a design flood event of a 0.5% AEP, flood risk will increase as sea levels rise, meaning that there was an increased risk to life, and access and egress issues during future design flood events. On a UK basis, the degree to which these conversations about long-term future risk for coastal locations are taking place is not known, including for decisions around the winter occupation of caravan sites.

Nearly a quarter of England's 4,500 km of coast is now defended (Sayers *et al.*, 2015) and several new schemes are currently being built or are planned, such as the £100m Southsea Coastal Scheme which stretches for 4.5 km from Old Portsmouth to Eastney. England has two of the world's 18 storm surge barriers; the Thames Barrier, which became operational in 1982, and a smaller barrier across the River Hull, which became operational in 1980. Both of these barriers protect low-lying land, and the associated communities, properties and assets, from coastal flooding. The Thames Barrier has been closed 195 times since it became operational in 1982 (correct as of January 2021). Of these closures, 107 were to protect against tidal flooding and 88 were to protect against combined tidal/fluviial flooding (EA, 2021b). In 2014, the Barrier was closed 41 times to protect against combined flooding and 9 times to protect against tidal flooding (EA, 2020b). The Hull Barrier has closed around 12 times a year since it was opened in 1980 (Mooyaart and Jonkman, 2017). Two smaller barriers are currently being built at Ipswich, Suffolk and Boston, Lincolnshire (Haigh *et al.*, 2020).

The sustained period of coastal flooding over the winter of 2013/14 provided a recent impetus for further defence improvements and new schemes. Despite the 5–6 December 2013 event producing higher sea levels along the UK east coast than in 1953 in many places, damages (and loss of life) were much less in 2013 due to improvements in flood defences, and flood forecasting and warnings (Wadey *et al.*, 2015); 720,000 properties were protected from the high sea levels by flood defences (EA, 2016b). However, flood defences were damaged during the 2013/14 season and the cost of repair (including fluviial defences) has been estimated to be approximately £147 million (EA, 2016b). The Thames Barrier was closed an 'exceptional' 50 times in the winter of 2013/14, the maximum recommended number, but this was predominantly due to high river flow. There is no statistically significant trend in past closures (Haigh and Nicholls, 2019).

There is evidence that major FCERM schemes are being put in place with standards of protection built in to protect against future flooding and coastal change conditions taking account of climate change (Wingfield and Brisley, 2017). Management options for coastal change focus increasingly on nature-based solutions. This approach recognises that the coastline is constantly evolving, and that climate change is one of many factors that affect habitats and species, and coastal assets and communities. In response, the coastline is now managed in a variety of ways that are sympathetic to protecting the coast and helping to conserve the natural environment (MCCIP, 2020).

Adaptive management approaches are being implemented regarding the long term resilience of recently constructed flood risk schemes (Wingfield and Brisley, 2017). The Thames Estuary 2100 (TE2100) Plan, approved by Defra in 2012, was developed to provide strategic direction for managing tidal flood risk in the Thames estuary to the end of the century. The Plan takes an adaptive approach based on a relative sea level rise estimate of 90 cm by 2100, but adaptable to differing rates of sea level rise up to 2.7 m by 2100. The TE2100 Plan is on a 5 yearly review cycle; the first review commenced in 2015 (EA, 2016e) and completed in 2017. The first full (10 year) review started at the end of 2018. The first phase of that work, monitoring and assessment of what has changed, was completed in 2020. The full (10 year) review project (including the economic case and updated version of the plan) is due for completion in 2022.

#### 5.5.2.1.2 Northern Ireland

In Northern Ireland there have been calls for a more strategic approach to coastal erosion risk management (Cooper, 2015). Northern Ireland does not have Shoreline Management Plans. Research commissioned by the Department of Agriculture, Environment and Rural Affairs and Department for Infrastructure in 2019 (Daera, 2018) identified the need to establish a coastal erosion baseline for the country to inform local development planning and development control, and allow for informed decisions with regard to the long-term management of coastal assets. This baseline analysis was published in 2019 (referenced in NICCAP2, (Daera, 2018)). It also highlighted the need for coastal erosion risk management to be a shared responsibility and suggested that the Coastal Forum could play a key role in informing the development of policy and strategy in this area including the delivery of a prioritised and coordinated monitoring programme to empower local decision makers. The second national adaptation programme, NICCAP2, highlights that the Coastal Forum will consider the findings of the baseline risk assessment and agree actions.

Daera and DfI commissioned a baseline study and gap analysis of coastal erosion risk management in Northern Ireland. The report identifies areas that may be vulnerable to coastal erosion in Northern Ireland. At Mount Stewart, for example, the National Trust has noticed increasing sea levels, and plans are in place to adapt to the rising sea levels of Strangford Lough. The National Trust has enhanced the existing Sea Plantation on the shores of the lough, however recent climate change studies have suggested that the Sea Plantation will struggle to protect the property. Due to this, the National Trust has begun a long-term plan to future-proof the property, and in particular the gardens, by preparing to allow tidal flats to encroach on what had previously been wetlands. To do this, National Trust have acquired land not at risk from extreme weather events and are preparing to relocate the car park. This site will then be replaced by a dense shelterbelt which will take over some of the role of the Sea Plantation (Daera, 2018).

#### 5.5.2.1.3 Scotland

In Scotland, Local Authorities have duties under the Coast Protection Act 1949 and Flood Risk Management (Scotland) Act 2009. These include responsibilities for implementing actions contained in the Local Flood Risk Management Plan and permissive powers to allow for the undertaking of any other protection works and actions.

SMPs are also in place in six of Scotland's 25 coastal Local Authorities (Angus, Dumfries & Galloway, East Lothian, Fife, North and South Ayrshire, and Scottish Borders) with several (such as Dumfries and Galloway and Scottish Borders) currently updating their SMPs.

Planning authorities in Scotland have a duty under the Climate Change (Scotland) Act to deliver the Scottish Climate Change Adaptation Programme, which addresses the risks set out in the Climate Change Risk Assessment (Scotland), including erosion and flooding risks to natural environment, infrastructure, people and built environment, and business (Scottish Government, 2017b).

Scotland's National Coastal Change Risk Assessment (CCRA) provides an evidence base of national coastal change. This summarised the last 130 years of coastal change across all of Scotland's erodible

shores (beaches, dunes and saltmarshes) and projected the changes forward to 2050 and 2100. The data and research outputs produced by Dynamic coast is intended to support the implementation of the National Planning Framework, Scottish Planning Policy and Flood Risk Management Planning, Local Development Plans, Land Use Strategy, National and Regional Marine Plans (Scottish Government, 2017a).

The 2020 Scottish Programme for Government includes a commitment to invest £12 million for coastal change adaptation over a four-year period from 2021/22 (Scottish Government, 2020c).

#### 5.5.2.1.4 Wales

As with England, SMPs are in place for the whole of the Wales coastline and are supported by Planning Policy Wales (2018) and the new Wales Flood and Coastal Erosion Risk Management Strategy (2020) which recognises risk from flooding and coastal erosion to coastal communities and highlights efforts to introduce interventions which use natural systems to reduce negative impacts (Welsh Government, 2018a, 2020c). This sets the overall policy framework for the Coastal Risk Management Programme and other measures to protect coasts. As detailed in H3, the revised Technical Advice Note (TAN) 15: Development, flooding and coastal erosion is due for publication in 2021, incorporating an update of requirements set out in TAN 14 on coastal planning, which has not been updated since 1998.

Following the coastal flooding in December 2013 and January 2014, Natural Resources Wales conducted a review of these events looking at first the impacts (NRW, 2014a) and then the lessons learnt, together with recommendations for the future (NRW, 2014b). In total, it is estimated that coastal defence structures in Wales suffered storm damage at around 65 locations in December 2013 and 110 locations in January 2014. The report identified that the damage and disruption to the coast and coastal communities was significant and the impact on those who have been affected is extremely distressing. However, the severity of damage and costs incurred could have been much worse. The Phase 2 report identified learning and lessons for the future and recommended action in six areas: (i) sustained investment in coastal risk management; (ii) improved information about coastal flood defence systems; (iii) greater clarity regarding the roles and responsibilities of agencies and authorities; (iv) an assessment of skills and capacity; (v) more support to help communities become resilient; and (vi) delivery of locally-developed plans in coastal communities.

As has been identified in Prosperity for All: A Climate Conscious Wales (2019), there are additional actions underway (Welsh Government, 2019f). The Welsh Government is working with the Wales Coastal Group Forum to develop a Coastal Adaptation Toolkit, which will support engagement on adaptation with local communities following lessons learned from Fairbourne. The Welsh Government has provided three years funding to the Wales Coastal Monitoring Centre to collate and analyse data on the changing Welsh coastline which will help to inform decisions and priorities for coastal adaptation and potential schemes, on a national basis. The Welsh Government also provided £150 million of funding to the Coastal Risk Management Programme, funding local authorities for a concentrated period of investment between 2019 and 2022 for coastal adaptation and risk management schemes. The programme supports local authorities in responding to the challenges of climate change and implementing the actions and risk management set out in the SMPs. This

programme also focusses on reducing current and future risk to homes and businesses whilst also providing wider benefits wherever possible.

These actions will be delivered via the new National Strategy on FCERM (Welsh Government, 2020c) and the Wales Coastal Risk Management Programme (Welsh Government, 2019b).

#### 5.5.2.2 Shortfall in current adaptation (H4)

At the moment, it is not known which communities are most likely to be lost under different future sea level rise scenarios, despite the fact the UK is now locked into centuries of further changes in sea level. Whilst there have been positive developments in national and local strategy regarding the management of coastal change across the UK as detailed above, what is missing is a dedicated programme of work to identify, and then create, plans for communities that may no longer be sustainable as sea levels rise. Transformational adaptation, including implementation of adaptive approaches and long term strategic planning is needed and a process to support this.

The following areas would, in our view, also benefit from further action to enhance understanding and management of coastal change:

- Across the UK, advances have been made in understanding risk, including the use of updated climate projections (UKCP18) to inform strategy and policy. The level of understanding and embedding of new projections varies across the UK. Flood risk management modelling and mapping is a mature industry with world leading advances in technology and knowledge informing this area. Coastal erosion is less well developed, although there has been notable progress such as Dynamic Coast: Scotland's Coastal Change Assessment. A more comprehensive evaluation of historic property losses is required, and coastal authorities need to establish and maintain a register of properties lost to coastal erosion to provide a more robust on-going record of the impacts of coastal erosion.
- A more-complete assessment of future changes in the wave- and storm surge-climate, based on improved atmospheric models, is required to improve understanding of natural variability and better isolate possible long-term trends. A better and more-accurate analysis of historical storm events and their impacts is required, which will lead to improved understanding of natural variability, which would allow trends due to climate change to be isolated.
- A better understanding of expected annual damages and event losses due to coastal sources, historically, today and in the future is also required to inform the national threat level (Haigh *et al.*, 2020).
- New national strategies for flood and coastal erosion risk management are in place, or in train, in England, Scotland and Wales that strongly promote nature based solutions, building and enhancing the resilience of communities, and adaptive pathways with a more explicit recognition of the need to address climate change than in the past. Delivery of these



strategies is now needed along with monitoring to understand the actions being taken and the impact they are having on managing risk.

- CCC (2018) highlights that some schemes to enable the implementation of Hold the Line policies are not cost-beneficial under current public sector funding regimes. Realigning coasts is also not happening at rates initially envisaged in England (CCC, 2018). As part of the review of SMPs, consideration should be given to barriers to implementing the plans as set out, and what should happen in cases where the SMP options are not being implemented as intended. It is not clear at the moment what happens in these cases.
- Related to the above, the process of managing such change involves complex issues around social justice that can only be addressed through effective governance, accountability and decision-making. Recent research published by the Environment Agency on community engagement in climate adaptation highlighted the importance of paying attention to local needs and conditions, the importance of clear, contextual and realistic engagement objectives and developing shared understanding about what engagement involves and what it is intended to achieve, prioritising places, partners and approaches that indicate potential to generate new learning, and creating mechanisms through which learning will be shared effectively (Kelly and Kelly, 2019). The Defra Policy Statement for England includes commitments to review current mechanisms and legal powers that Coastal Planning Authorities can use to manage the coast, and to explore the availability and role of financial products or services that can help people or businesses to achieve a managed transition away from areas at very high risk of coastal erosion. Again, the outcomes of this review and implementation evidence is required to address the current shortfall in this area.

#### 5.5.2.3 Adaptation Scores (H4)

Table 5.20. Adaptation Scores for risks to the viability of coastal communities from sea level rise			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially	Partially	Partially	Partially
(Medium confidence)	(Low confidence)	(Medium confidence)	(Medium confidence)

#### 5.5.3 Benefits of further adaptation action in the next five years (H4)

Our view is that there will be benefits from a ‘national conversation’ about risk acceptability, and local discussions, particularly in England and Wales, to identify the communities at risk and then develop plans for these communities including providing clear messages about how a process of change will be delivered. This brings in requirements in relation to the following areas, which Defra (Ballard *et al.*, 2018) recently highlighted to improve coastal change in adaptation, but these apply equally to other parts of the UK:

- Strategic planning
  - Interpretation of and required actions relating to Coastal-Change-Management-Areas.
  - How to bring adaptation planning in line with SMP delivery.
  - Improved strategies across SMPs and policy unit boundaries.
- Legal
  - Perceived needs related to legal issues include guidance on and support with articulating a clear legal framework around adaptation planning, roll back and other adaptation policy implementation processes.
- Funding – perceived needs related to funding include guidance on and support with:
  - Developing and delivering long-term investment strategies.
  - Full suite of financing options available.
  - How to best incentivise roll back.
  - Development of new financial products that could enable vulnerable communities to adapt cost-effectively.
- Community engagement
  - Raising awareness of SMP and policies generally, including how to convey that there may be risks with policy non-deliverability due to longer term funding gaps.
  - Securing funds for dedicated and skilled community engagement individuals to reduce future risk and raise awareness.
  - Securing engagement and buy-in from elected councillors.
  - Strategic planning for supporting community infrastructure.
  - Strategic planning for caravan park businesses and their inhabitants.
- Monitoring
  - Perceived needs related to monitoring include guidance on and support with monitoring coastal erosion, monitoring property and infrastructure at risk and when lost to coastal erosion (including temporary infrastructure e.g. caravans).

#### 5.5.3.1 Indicative costs and benefits of additional adaptation (H4)

In general terms, the literature reports that coastal adaptation is an extremely cost-effective response, significantly reducing residual damage costs down to very low levels (Hinkel *et al.*, 2014). However, in locations with very few properties, such measures often have benefit-cost ratios lower than one. This may contribute to decisions that a community's long term viability is unsustainable, when viewed from the perspective of economic efficiency. However, many more issues are involved in such cases, such as threat to life should existing or upgraded defences be breached, and there is a need for any economic analysis to consider the wider issues, and also consider different perspectives including social justice.

#### 5.5.3.2 Urgency scores (H4)

Given the potentially very high levels of future risk and lack of a full policy framework to consider long-term viability of communities in order to drive the risk down to a low level by 2100, more action needed scores have been assigned to England, Wales and Scotland. In Northern Ireland, the

lack of an erosion baseline and strategies for addressing long-term change points to the need to further assess the level of risk to identify how much adaptation is needed.

**Table 5.21.** Urgency Scores for risks to the viability of coastal communities from sea level rise

Country	England	Northern Ireland	Scotland	Wales
Urgency Score	More action needed	Further investigation	More action needed	More action needed
Confidence	High	Low	High	High

#### 5.5.4 Looking Ahead (H4)

- A UK/national assessment identifying which locations are likely to be unsustainable in the long term is required, enabling planning to commence regarding any potential relocation of communities.
- Further advances in modelling and mapping are required regarding coastal erosion to enhance understanding and enable a more consistent assessment across the UK.
- Best practice developed across the UK regarding community engagement and messaging needs to be widely shared, facilitating knowledge transfer and improving planning for the relocation of communities. This should enable high levels of awareness and understanding of the implications for individuals as well as the wider community.

#### Box 5.3. CASE STUDY: Fairbourne and coastal change

Fairbourne is well known for being the first community in the UK whose long term future has been deemed unsustainable due to climate change. As the impacts of climate change are realised, it is likely that other coastal communities will be faced with the same uncertain future and therefore lessons can be learned from coastal risk management in Fairbourne.

Fairbourne is a small community village on the west Wales coast in the ward of Arthog in Gwynedd. It houses 461 residential and business properties with a population of around 700 that increases to 3,000 in the summer with the influx of visitors. Located at the mouth of the Afon Mawddach, Fairbourne was built as a seaside retreat on newly defended and reclaimed land during the late 19<sup>th</sup> and early 20<sup>th</sup> century (Bennett-Lloyd *et al.*, 2019).

##### Hazard

Despite defences protecting its estuarine and coastal frontages, rising sea levels as a result of climate change suggest that much of the village of Fairbourne would be below normal high tide levels within the next 50 years, indeed many properties are already below the Mean High Water springs level. There are also high groundwater levels and a high risk of surface water flooding in the village. The SMP2 policies for the area for periods 2055 to 2105 indicate that there may be a need for part, if not all of the village, which is currently protected by the estuarine embankment and sea wall, to relocate or disperse elsewhere (Hold the Line policies moving to Managed Realignment or No Active Intervention). The implications of these policies have generated

significant concerns for the local community, Gwynedd Council and Welsh Government (Bennett-Lloyd *et al.*, 2019).

### Future Risk

Fairbourne is already at risk of flooding as its ground levels are lower than the average high spring tide level; this is reached twice a month during periods of spring tides. Risk is even greater if high tides coincide with a storm surge and/or large waves, for example as experienced on the coast of West Wales on 3–4 January 2014 (Sibley *et al.*, 2015). Therefore, the safety of its residents is very much reliant on existing defences. The Fairbourne Moving Forward Partnership (2019) cited projections of sea level rise at Barmouth (3 miles north of Fairbourne) of 0.7 m by 2100 relative to 1990 levels with a scenario consistent with 4°C global warming by 2100<sup>7</sup> and 0.9m by 2100 with a higher scenario<sup>8</sup>. Mean sea level is likely to increase by 0.76 m to 1.03 m in Gwynedd by 2100 relative to 1981–2000, based on projections<sup>9</sup> consistent with global warming slightly above the CCRA3 scenario of 4°C warming by 2100. For a scenario of approximately 2°C warming by 2100, sea level in that part of the coast is projected to rise by approximately 0.4 m by 2100 (Palmer *et al.*, 2018; Welsh Government, 2021d). The latest projections have identified no evidence for significant changes in future storm surges (Met Office, 2018).

### Public Health and Built Environment Impact

Rising sea levels mean it will become increasingly difficult to protect the village. In the long term, maintaining and increasing flood defences would not only be costly, but would also lead to increased risk to life should the defences fail. It has therefore been considered that it is not possible to maintain an acceptable standard of flood protection in the future. Predictions, accompanied by evidence from local monitoring show that by 2054, it is unlikely to be safe or sustainable for permanent residents to remain in Fairbourne. However, it is possible that a significant breach in the sea defences could occur before 2054, requiring the relocation of the village. Plans are being put in place to address this situation should it arise. In the meantime, sea-level rise will continue to be monitored.

Currently there are 461 properties at risk of tidal flooding and 58 properties at risk from fluvial flooding in Fairbourne. The majority of local residents are over 60 and most own their own homes. House prices fell substantially when the SMP2 policies were first publicised, bringing concerns around property blight. Key impacts for communities relate to a loss of a sense of security and financial loss that could have impacts for wellbeing and mental health resulting from these concerns, decreasing community cohesion and change in demographics as people move away, loss of community facilities, and loss of tourism and recreation that affect the economic viability of Fairbourne as a resort.

A recent survey conducted by the Fairbourne Moving Forward Social and Economic Adaptation Group identified that 86% of those interviewed said their level of mental health had declined, 82% said their physical health had deteriorated, 94% said their financial position had deteriorated, 85% said they didn't feel positive about the future and 98% said they no longer feel in control of their future and feel they cannot look after themselves in their later years (Bennett-Lloyd *et al.*, 2019).

<sup>7</sup> UKCP09 medium emissions scenario, 95<sup>th</sup> percentile

<sup>8</sup> UKCP09 high emissions scenario, 95<sup>th</sup> percentile

<sup>9</sup> UKCP18 marine projections, 70<sup>th</sup> and 95<sup>th</sup> percentile driven by CMIP5 climate projections with standard RCP8.5 concentrations – note that this gives a lower rate of global warming than the UKCP18 land projections, which are based on a wider set of climate models and also consider uncertainties in carbon cycle feedbacks.

### Response to Risk

In 2013, shortly after the SMP2 document was adopted by Gwynedd Council, a multi-agency group was formed under the Fairbourne: Moving Forward (FMF) banner. The aim of FMF was to *'address the complex issues identified and to draw upon experience and knowledge from a range of organisations and the local community'*. Organisations represented on FMF are Gwynedd Council, Natural Resources Wales, Arthog Community Council, Welsh Government, Fairbourne Facing Change community action group (disbanded in 2018), Network Rail, Welsh Water, Snowdonia National Park and Royal Haskoning DHV.

Over the last seven years, FMF has conducted a twin-track of actions to i) support the local community; and ii) work with stakeholders to develop a planned approach to the decommissioning.

Community actions have involved: awareness-raising meetings for residents and businesses, regular drop-in surgeries for local residents, counselling for any resident experiencing mental health issues (funded by FMF), launch of the [www.fairbourne.info](http://www.fairbourne.info) website and project Facebook page, production of regular issues of newsletters, mock evacuation exercise held in Friog and Fairbourne Village Hall and the development of a Fairbourne Multi-Agency Response Plan to evacuate residents from Fairbourne in the event of a significant flood.

Stakeholder actions have included (i) the establishment of dedicated working groups to address issues faced by the community; (ii) publication of FRM project review reports; (iii) securing funding from Welsh Government to conduct a feasibility study and produce a business case to establish a community interest company for Fairbourne; (iv) Governance workshop with stakeholders; (v) Climate Change Adaptation sub-group established by Gwynedd and Anglesey Public Service Board; (vi) research conducted on a Recovery and Resettlement Plan for residents; (vii) Preliminary Coastal Adaptation Masterplan produced; and (viii) workshops held with stakeholders to discuss the Masterplan.

Following the production of the Preliminary Coastal Adaptation Masterplan for Fairbourne in 2018, Gwynedd Council and FMF have been working with the community to develop a Framework for future planning covering five themes: flood risk management, people and the built environment, infrastructure, business, and natural environment management. Working groups are also being established for each theme to address relevant issues.

### Key messages

Whilst Fairbourne is one of the first communities in the UK to be identified as unsustainable in the long term in policy documentation, evidence from research undertaken in relation to other locations facing similar issues with coastal realignment have identified the importance of appropriate and early community engagement. This gives time to consider and accept adaptation as an alternative to defence (Defra, 2012b), address challenges with gaps between policies and deliverable plans (Shifting Shores +10 research), and enable progressive learning approaches for successful longer term outcomes (*Coastal Communities 2150* EU project).

There were initial concerns around the way that engagement associated with SMP2 policy development and delivery had been carried out. This has improved considerably since measures have been put in place to both support the community and increase stakeholder engagement. (Bennett-Lloyd *et al.*, 2019).

The Welsh Government published a Fairbourne Coastal Risk Learning Project report in 2019 that aimed to learn from the experience of Fairbourne to better understand how to plan for and

manage climate change and adaptation elsewhere (Bennett-Lloyd *et al.*, 2019). This had the following key conclusions for other areas:

- There are clear points to take forward into any review of SMPs, especially surrounding the policies of No Active Intervention or Managed Realignment where they impact on communities or represent a shift from previous policy direction. A closer examination of the processes and consequences around policy-setting and policy implementation needs to be undertaken to inform how to engage with these communities and wider stakeholders affected by these policies.
- It is recommended that the earlier published engagement guidance for SMP development is reviewed and the learning points incorporated with regards to implementation and communication.
- Governance and decision-making has emerged as a key area of concern. The Fairbourne project has broken a great deal of new ground and learning has been continuously evolving. Whilst the SMP2 has been the trigger for the change-management processes underway, the mandate goes far wider than traditional coastal risk management and cuts to the heart of the Well-Being of Future Generations legislation, well-being planning and the role of Public Service Boards (PSBs).
- There needs to be further consideration of how PSBs can play an active role in the oversight and championing of climate change adaptation planning consistently across Wales, learning lessons from the work currently being undertaken through the Gwynedd and Anglesey PSB and being supported by Gwynedd Council and Natural Resources Wales.
- Early, progressive and inclusive engagement with communities is of key importance to maintain community cohesion and support health and well-being.

Additional issues which chime with the above were highlighted in more recent research published in 2020 (Buser, 2020). This sets out the challenges associated with climate change adaptation involving multiple agencies; the potential for uneven processes and differential outcomes according to individuals' circumstances, and the need for a robust communication plan that involves the media.

## 5.6 Risks to building fabric (H5)

Climate hazards that can damage building fabric include subsidence caused by drought and dry soil, excessive moisture due to flooding and heavy rain, and structural damage due to high winds. In terms of insurance costs and costs to households, subsidence represents the biggest impact. The presence of at least some relevant building standards across all four UK countries means that the present-day risk is being considered for new build homes or those undergoing refurbishment. However, there is little evidence that the future risks from climate change in scenarios of either 2°C and 4°C global warming by 2100 are yet being integrated into planning, building design or retrofit, potentially locking in homes to some future risk.

The hazard posed by landslides is also included in this risk. This includes areas with potentially unstable landscapes resulting from industrial activity, namely coal tips.

The impact of climate change on these specific hazards (weather conditions) is highly uncertain as they are not well described in climate models or climate scenarios.

### 5.6.1 Current and future level of risk (H5)

This risk considers damage to dwellings from moisture, high winds, subsidence due to extreme weather events, and insect damage which can be linked to warmer seasons. The risk is primarily concerned with homes and costs to households. Damage to infrastructure is considered in detail in Chapter 4 (Jaroszweski, Wood and Chapman, 2021). Damage to building fabric entails costs to the home owner for repair. In addition, damp buildings cause harm to health and wellbeing, and damage to dwellings from high winds can also risk injury.

The evidence regarding this risk is divided by the type of climate hazard for current and future risks. In most cases it has not been possible to find specific evidence by UK country, so the analysis for this risk is largely described at the UK level, with specific issues for individual countries highlighted where appropriate. In addition, not all elements of the methodology have been fully conducted due to the evidence gaps.

#### 5.6.1.1 Current and future risks of moisture damage – UK (H5)

The main causes of indoor moisture accumulation in buildings are:

- Poorly insulated structures which can have low surface temperatures.
- Vapour concentration in the indoor environment which depends on the water content of outdoor air, moisture generation and ventilation. High vapour concentrations, especially if combined with low surface temperatures, can lead to mould growth.
- Water ingress which is associated with flooding but also with rainwater or groundwater penetration through building materials or defects. Building materials with a porous external surface, such as exposed bricks, can absorb rainwater and groundwater. Cracks in the building fabric and poorly-detailed junctions are also a cause of rainwater ingress, which can lead to damp, wood rot in timbers, corrosion in metal elements, as well as frost damage and salt efflorescence in the building fabric.

Vapour concentration gradients (changes in the proportion of water vapour in the air) and the effect of wind or solar radiation can contribute to the drying of the building fabric. Inhibiting these drying mechanisms – for example, by adding materials with higher vapour resistance – could lead to moisture accumulation at the interface between these building materials. Excess moisture accumulation within the building fabric can lead to mechanical failure of the building (D'Ayala and Aktas, 2016).

Household heating systems lead to increased household temperatures, and are standard in most households in the UK. However, the level of heating and moisture varies with the level of insulation. Energy-efficient interventions reduce moisture risks, in particular, indoor mould growth, as they lead to an increase in indoor temperatures. However, if improperly installed, these interventions can lead to the exacerbation of such risks (see also implications for Net Zero).

- Reduction of air infiltration without considering additional ventilation can lead to higher indoor vapour and mould growth (McGill *et al.*, 2015; Sharpe *et al.*, 2015).

- Thermal bridges at junctions can lead to localised mould growth (Altamirano-Medina, 2016; Marincioni *et al.*, 2016).
- Increase of rainwater penetration at poorly-detailed junctions between insulation system and existing building fabric can lead to localised areas of excess moisture accumulation. There is evidence of moisture-related failure in both insulated solid walls and cavity walls, due to rainwater penetration associated with poor detailing and installation, lack of maintenance, poor design and specification (Heath, 2014; King and Weeks, 2016; BRE, 2019).
- Low temperatures at the interface of building materials, depending on the vapour control provided by the insulation system, can lead to mould growth and condensation.
- Reduction of drying of excess moisture, depending on the drying potential of the insulation system (Marincioni *et al.*, 2014), can lead to mould growth or damp.

Future moisture risks from climate change relate to increases in precipitation. It is very likely that heavy rainfall events will increase in all countries (see Chapter 1: Slingo, 2021). Changes in the absolute moisture content of the outdoor air may mean that increased ventilation may be required to remove moisture from the indoor environment adequately. Heavy rainfall events will increase rainwater ingress in the building fabric (Orr *et al.*, 2018). Wind-driven rain is associated with winter storms and the intensity of rainfall in storm events is projected to increase, although the effect of climate change on storm frequency and storm tracks is uncertain. Climate change is likely to lead to increases in wind driven rain, particularly in Scotland and northern England. Climate change is also likely to increase all types of winter rainfall and therefore there is increased likelihood of increase in the water penetration of vertical walls of dwellings.

The impact of these risks at a population level can be substantial, however there is little quantified evidence. Heavier rainfall would increase the mechanical damage to buildings and be detrimental to the health of occupants. Alternatively, there could be a minor benefit associated with milder winters, as the higher surface temperatures might reduce the risk of mould growth, provided there is sufficient ventilation to remove moisture from the indoor air. Also, projected temperature increases should enable damp buildings to dry faster, provided they have sufficient ventilation.

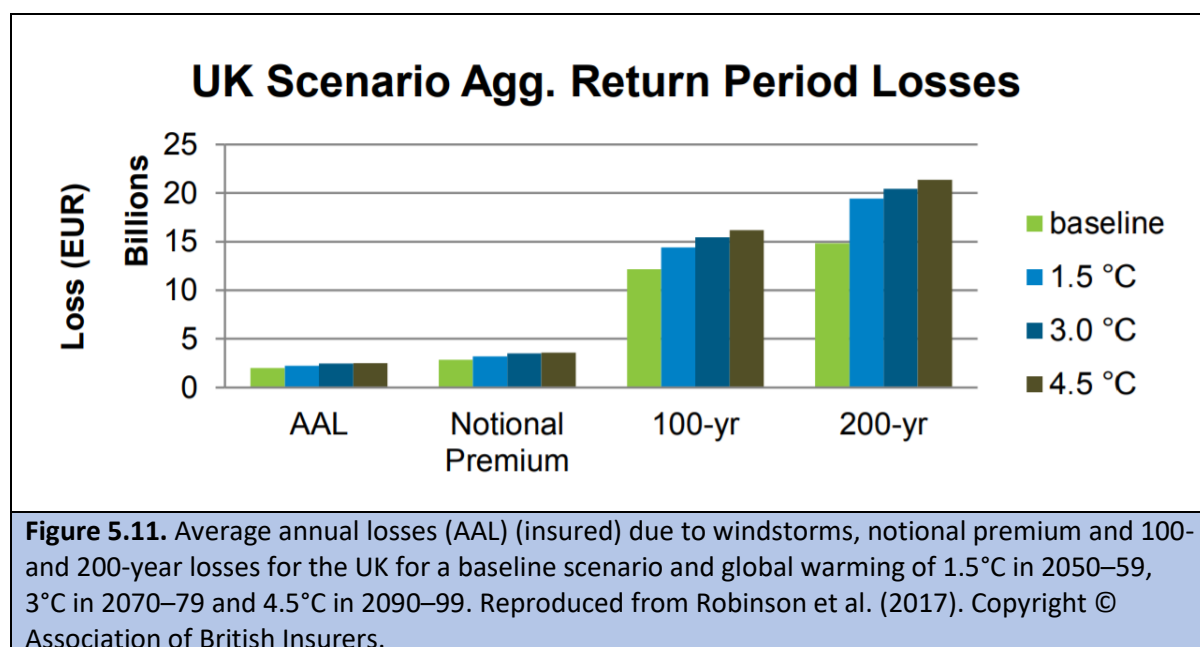
#### 5.6.1.2 Current and future risks of wind damage – UK (H5)

Wind storms are among the most damaging extreme events in the UK (ABI, 2017). Climate change has the potential to alter the frequency and intensity of these storms and thus affect the distribution of insured and uninsured losses. However, the projections of these changes are uncertain, particularly whether the North Atlantic storm track could shift northward in the future, resulting in fewer mid-latitude storms.

Some studies have indicated a small increase in the number of wind storms affecting the UK, with the the frequency and intensity of the most extreme windstorms increasing during the winter months. Robinson *et al.* (2017) considered projected changes in frequency and intensity of windstorms, and looked at the average annual loss (AAL), i.e. annual insured loss aggregated over an entire year, the 1.0% exceedance probability (1 in 100-year) loss, and the 0.5% exceedance probability (1 in 200-year) loss (Figure 5.11). The results indicated a change in the overall AAL of 11%, 23%, and 25% for global warming levels of 1.5°C in the 2050s, 3.0°C in the 2070s, and 4.5°C in



the 2090s, respectively. The analysis also indicated a possible increase of up to 30% in the 1% exceedance probability (1 in 100-year) loss and up to 40% in the 0.5% (1 in 200-year) exceedance probability loss with 4.5°C warming in the 2090s, though the distributions of these changes are not equal across the country.



There is limited evidence regarding the impact of wind damage to dwellings in the UK, however some evidence from the Scottish 2019 Progress Report by the CCC highlights that the vulnerability of the Scottish housing stock to extreme wind and rain is declining (CCC, 2019e). Rates of domestic building disrepair have declined over the last ten years. However, there has been no significant difference in homes reporting dampness since 2002 – reported to be approximately 4% in 2016. In Scotland there are limited provisions in building standards for making changes to existing buildings with adaptation measures for the impacts of extreme wind and rain (CCC, 2019e). Current exposure to wind-driven rain in Scotland ranges from ‘Moderate’ (some east coast areas) to ‘Very Severe’ along much of the west coast and Scottish Islands.

#### 5.6.1.3 Current and future risks of subsidence - UK (H5)

Subsidence is caused by a reduction in moisture in the ground beneath a building, causing shrinkage and the development of cracks within the structure of the dwelling (Crawford, 2018). Soil type (e.g. clay soils) and local vegetation are the dominant cause of subsidence. Clay soils with high shrink-swell potential underlie much of the densely populated areas of London and the South East of England. Other areas can also be susceptible to subsidence, for example the Vale of York and the Cheshire Plain. Older buildings and buildings with shallow foundations are at greatest risk. Factors that exacerbate the risks of subsidence for homes include prolonged hot spells which dry out the soil, removing moisture which impacts the buildings structure (Crawford, 2018). In addition, the effect is more marked where buildings are close to trees, which can remove moisture from the ground as far as 6 m below the surface (Gething, 2010).

The Association of British Insurers reported the 2018 hot summer was associated with over 10,000 claims totalling £64 million (ABI, 2018). These were the highest reported figures since the 2003 and 2006 hot summers and represented a 350% increase from the previous quarter. Subsidence claims were highest in the South East (ABI, 2018). Compared with the previous quarter, with 2,500 claims, the jump to 10,000 was the highest reported change quarter-to-quarter since records began (ABI, 2018).

There have been few recent assessments of the costs of subsidence since 2016. Hunt and Taylor (2006) estimated impacts of £5–15 million in the 2020s, rising to £25–185 million in the 2050s and £115–315 million in the 2080s. A recent study by BGS (2020) on the risks to soils indicated that clay soils that shrink and swell with changes in moisture are going to become increasingly susceptible to subsidence in the coming century and beyond.

Subsidence is also a risk for houses in areas with past mining activities, and subsidence events can be triggered by heavy rainfall. Following Storm Christoph in January 2021, houses in Skewen in South Wales were flooded following a mine shaft ‘blow out’, caused by water building up in the mine shaft which had then collapsed (Coal Authority, 2021).

#### 5.6.1.4 Current and future risks of landslides - UK (H5)

Landslides and landslips represent additional risks to dwellings throughout the UK and can be associated with heavy rainfall events. In Wales, past mining activities have left a legacy of coal tips at risk of landslides which present both a physical and a chemical hazard. Following heavy rain during Storm Dennis in February 2020, a major slope failure occurred at Llanwonno tip near coal tip near Tylorstown, South Wales (Smith, 2020). A number of minor landslips also occurred at other tips in South Wales. The Welsh Government statement on coal tip safety (Welsh Government, 2021e) highlighted the difficulties in reducing the risk of slope failures. Substantial shortcomings in current legislation and the fiscal framework regarding tip inspections and remediation have been identified. Regular inspections of disused tips is not currently mandated, but an approach to risk assessment of coal tips is being developed and implemented. Tips are being categorised according to both their level of inherent risk and also whether the location poses a risk to people or critical infrastructure, or a risk to the environment such as rivers or other infrastructure, or are situated in a remote area (Coal Authority, 2020). There are over 2,000 coal tips in Wales, predominately in the South Wales Valleys; 294 have been identified as high risk (Fairclough, 2021). With annual mean rainfall having increased in Wales, especially in South Wales (Chapter 1: Slingo, 2021), we suggest that it is possible that climate change may have already increased the risk of future slope failures. Heavy precipitation is projected to increase (Chapter 1: Slingo, 2021), which could further magnify the risk.

#### 5.6.1.5 Lock-in and potential thresholds (H5)

There is a risk of lock-in associated with current dwellings that are not resilient to extreme weather, and the risk that new buildings are built without consideration of extreme weather impacts and appropriate mitigations. A large number of new houses are planned, and there is a risk that these are not resilient to damp, high winds and subsidence. Subsidence tends to be a greater risk for older properties, but is a risk for new development on clay soils.

#### 5.6.1.6 Cross-cutting risks and interdependencies (H5)

This risk overlaps with the risk on flooding (H3) which also address damage to dwellings and costs to households.

This risk also overlaps with damage to buildings that are part of the health and social care systems (H13) and schools and prisons (H14) and part of our cultural heritage (H12).

#### 5.6.1.7 Implications of Net Zero (H5)

Net Zero policies that improve energy efficiency in housing are likely to affect risks associated with moisture. Creating low-energy buildings with increasing amounts of insulation and airtightness can lead to an increased risk of moisture-related damage to the structure and internal environment (BRE, 2016b; May and Sanders, 2017). Therefore, if strategies that address Net Zero do not consider additional ventilation they are likely to lead to higher indoor vapour and mould growth.

The CCC's sixth carbon budget pathways for reducing emissions in the UK take into account the need to assess ventilation and passive cooling alongside energy efficiency measures when retrofitting existing residential buildings (CCC, 2020).

#### 5.6.1.8 Inequalities (H5)

Low income households are less likely to have insurance cover in general (Defra, 2015a). There is less evidence regarding home owners and insurance for property damage. Private renters may be affected by building damage and are reliant on their landlords having appropriate insurance cover. Reasons for low uptake of insurance include financial constraints but also misperceptions of risks, and also a lack of trust that insurance companies will pay up (Penning-Rowsell, 2019).

#### 5.6.1.9 Magnitude scores (H5)

There is little quantitative information of impacts at the national level. The prevalence of damp in dwellings is high. The costs of wind damage to dwellings is not publicly available. The costs of subsidence to households (in terms of insurance claims) was estimated to be £5–15 million in the 2020s.

The magnitude score reflects the greatest magnitude across each of the three climate hazards by country. Important regional differences occur in the projections of risk. Thus, risks for subsidence are largest in the south of England and the magnitude of these impacts are judged as becoming high in the 2080s. The risks for damp are highest in Scotland and Northern Ireland but the overall score is judged as being medium. The risk of driving rain is a concern for Scotland and the north of England.

The magnitude scores for future risks are uncertain due to the lack of confidence in climate scenarios for these hazards, particularly regional changes in the frequency and intensity of extreme winds, driving rain, drought (see Chapter 1: Slingo, 2021). These risks are not well described in

climate models as they relate to local weather patterns. As such, the future magnitude scores are based on expert judgement only.

**Table 5.22.** Magnitude score for risks to building fabric

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	Medium	Medium	High	High
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Medium	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Medium	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Medium	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

## 5.6.2 Extent to which the current adaptation will manage the risk (H5)

### 5.6.2.1 Effects of current adaptation policy and commitments on current and future risk (H5)

#### 5.6.2.1.1 UK-wide

Building standards are the main strategy to address resilience to extreme weather in new dwellings or existing dwellings having alterations. The Building Regulations across the UK contain requirements that the building fabric and the health of the occupants should not be affected by moisture from the ground (including flooding), strong winds (Part 1A on loading), wind-driven precipitation and surface or interstitial condensation.

The current update of BS 5250 (British Code of Practice for Control of Condensation in Buildings) is based on a more integrated approach on moisture in buildings which does not consider elements in isolation, but as part of a whole-house approach, as described in the White Paper on Moisture in Buildings (May and Sanders, 2017). The BSI White Paper on Moisture gives an overview of current assessment for regulations and standards on this topic.

There are new frameworks on the retrofit of existing buildings, such as Publicly Available Specification (PAS) 2035:2019 (BSI, 2019), which considers adaptation in a broader context. PAS 2035 mentions the responsibility of designers to assess future climate vulnerability and identify adaptation options.

#### 5.6.2.1.2 England

There are standards and regulations to prevent excess moisture in buildings as set out above. The Ministry of Housing, Communities and Local Government (MHCLG) has commissioned an analysis of the robustness of the available guidance in Part C regarding building resistance to moisture, and the development of relevant guidance on the insulation of existing buildings in England. Although not explicitly considering adaptation to a future climate, the review assessed the robustness of build-ups against moisture and suggested measures for improving this robustness (MHCLG, 2019d), as well as in respect to rainwater protection. However, the suggestions considered an elemental approach, where measures were assessed in isolation, and the influence of interactions between different measures was not considered. For example, the assessment did not consider the increase in runoff associated with improving the water resistance of a wall, which can lead to an increase of the hydrostatic pressure at cracks and defective details, an important parameter for rainwater penetration (Lacasse *et al.*, 2019).

There are few government incentives for adapting existing homes, although some tools and guidance are available for rental homes, such as the Decent Homes Standard and the Housing Health and Safety Rating systems (HHSRS), which include damp and mould growth, and thermal comfort and excess heat.

The second National Adaptation Programme (Defra, 2018c) does not include any specific actions to manage the risks to building fabric from driving rain, wind or other hazards beyond flooding and heat.

#### 5.6.2.1.3 Northern Ireland

The second national adaptation programme for Northern Ireland (NICCAP2) (Daera, 2019) includes a high level objective to ensure that 'houses and buildings are resilient to the impacts of flooding and extreme weather'. The actions listed in relation to the outcome focus mainly on managing flood risk, whereas there are no specific actions listed for managing other risks to building fabric like driving rain or wind.

Northern Ireland has its own building standards (Building Control Northern Ireland, 2012) for new buildings. Similar to other jurisdictions in the UK, Technical Booklet C stipulates the requirements of building components to resist moisture from the outside.

To our knowledge, there is no strategy for retrofitting existing buildings to improve resilience to extreme weather.

#### 5.6.2.1.4 Scotland

Building standards for new buildings are in place for flood resilience, moisture penetration from heavy rain, heating, ventilation and condensation, and were revised in 2019.

The Scottish Government has a number of standards for building quality:

- The Scottish Government Tolerable standard provides a minimum condemnatory standard which all houses in Scotland must meet. The standard includes being substantially free from rising and penetrating damp as well as having satisfactory thermal insulation (defined as the presence of loft insulation where a property can have it).
- The Repairing Standard applies to private rented housing and requires houses to be wind and water tight and in all other respects reasonably fit for human habitation, and the structure and exterior of the house (including drains, gutters and external pipes) to be in a reasonable state of repair and in proper working order.
- The Scottish Housing Quality Standard requires social housing to be in a reasonable state of repair and to have a minimum standard of energy efficiency. Registered social landlords are also required to be working towards the Energy Efficiency Standard for Social Housing. These policies require houses to be in a good physical condition reducing water penetration and heat loss, which reduces the energy required to heat homes and increases their resilience to climate change.

A strategy for retrofitting existing buildings to improve resilience to extreme weather is being developed as part of Scotland's second statutory Adaptation Programme, 2019 (Scottish Government, 2019a). Scotland's draft Infrastructure Investment plan (published Feb 2021) also includes explicit recognition of the likely impacts of climate change on infrastructure and the need to 'adapt current infrastructure and design future assets to be more resilient to the effects of climate change' (Scottish Government, 2021).

#### 5.6.2.1.5 Wales

The Welsh Government's adaptation plan, Prosperity for All: A Climate Conscious Wales, sets out a commitment to influence the design of homes and buildings to protect them from the impacts of climate change. However, the focus for the commitment is on the risks from overheating in the home. Nevertheless, it is stated that climate adaptation will be considered for any future building regulation reviews, including actions to tackle risks to building fabric.

Under the Clean Air Plan for Wales (2020), research work is also planned to examine the resilience of buildings in Wales to climate driven impacts and provide practical recommendations for risk based adaptation (Welsh Government, 2020a) (see also risk H7).

Building standards are in place for flood resilience, moisture penetration from heavy rain, heating, ventilation and condensation.

### 5.6.2.2 Adaptation shortfall (H5)

Overall, climate change represents a range of challenges to improve buildings and housing quality (in addition, see H1 above on overheating and H3 on flooding). These challenges have generally not been considered holistically. The presence of at least some relevant building standards across all four UK countries means that the present-day risk is being considered for new build homes or those undergoing refurbishment. However, there is little evidence that the future risks from climate change are yet being integrated into planning, building design or retrofit, for pathways to either 4°C or 2°C global warming by 2100. This lack of long-term policy is likely to be locking-in new developments to some future risk, but as set out above, it is also unclear what the size of the future risk is.

### 5.6.2.3 Adaptation Scores (H5)

The assessment of current adaptation scores is based on the current building standards in each country, which in the most part address damp (excessive moisture), but are insufficient at present to address future climate risks. That is, future climate change is not taken into account.

<b>Table 5.23. Adaptation scores for risks to building fabric</b>			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially	Partially	Partially	Partially
(Medium confidence)	(Medium confidence)	(Medium confidence)	(Medium confidence)

### 5.6.3 Benefits of further adaptation action in the next five years (H5)

Improving housing quality has multiple benefits. There are direct benefits to health and wellbeing in addition to reducing household costs. The health burden from damp homes in particular is high.

Subsidence tends to be a slowly progressing threat, and most adaptation is reactive, in the form of repair once major problems emerge. There is well established information on the costs of reactive adaptation from subsidence insurance claims (see above), and indeed insurance is an adaptation response to current and future risks. There are potential benefits from more proactive approaches, with most of the literature focusing on monitoring, measurement and prediction (e.g. Erkens and Stouthamer (2020)), and these are a low-regret option in national adaptation planning and awareness raising to households. There is a wider literature on the costs and benefits of direct intervention measures to reduce subsidence, but most of this is focused on human induced subsidence (e.g. water related). For the shrink swell subsidence of most relevance to the UK, the main options are centred on proactive approaches already in use, e.g. vegetation control (trees) and local water management. For high risk areas, these are likely to be low regret.

An important response to windstorm risks is household insurance, which acts as a risk spreading mechanism for extreme wind events. The evidence from tropical wind storms indicates that retrofitting (for increased storm intensity or frequency from climate change) has high adaptation costs, especially for roofing upgrades (RMS, 2009), although it can lead to high benefits. There is less evidence for Europe, but this tends to report similar findings (Hunt and Anneboina, 2011; UBA, 2012). These sources indicate reasonable benefit:cost ratios (at least for some options) (BEIS, 2019b; Spinoni *et al.*, 2020). For household options, costs are lower in new builds, and can include siting and orientation, design and materials. The potential for increased building codes to cope with more intense windstorms is considered a low-regret option, however a review (ECONADAPT, 2017) has identified that benefit to cost ratios vary significantly with the risk level, the marginal costs of higher resilience, the existing cost and life-time of the asset, the costs of retrofitting based on local costs of materials and labour, and on the discount rate.

For damp or excessive moisture due to flooding, and intense or driving rain, the main current approach for managing risks for new buildings is through building standards and there has been recent research for moisture in buildings (MHCLG, 2019d). As highlighted above, there are potential benefits of a more integrated approach on moisture in buildings as part of a whole-house approach and accounting for the changing climate and potentially greater risks over time, although there would need to be an analysis of the potential costs and benefits of the climate uplifts, taking into account the long life-times and potential lock-in for new builds, but also the cost premium and nature of benefits (future, uncertain) (May and Sanders, 2017). The benefits of further adaptation for the existing building stock is highly variable and less well characterised, and there appears to be less economic evidence on potential options: this is identified as a potential gap.

Appropriate guidance and tools to support decision-making appear to be lacking, and are needed for the implementation of adaptation measures in the next decade in order to avoid lock-in with inappropriate housing designs.

#### 5.6.3.1 Overall urgency scores (H5)

There is a lack of research on this risk and the degree of future risk is difficult to determine at the present time, therefore it is evaluated as needing further investigation across the UK.

There is also lack of evidence regarding the prevalence of damage to dwellings, and household costs for damage associated with climate hazards to building fabric. The magnitude and direction of future changes in the frequency or intensity of the climate hazards is also uncertain. Further research could enable more relevant climate information for decision makers.

<b>Table 5.24. Urgency scores for risk to building fabric</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency Score</b>	Further investigation	Further investigation	Further investigation	Further investigation
<b>Confidence</b>	Medium	Low	Medium	Medium



#### 5.6.4 Looking Ahead (H5)

The influence of climate change on windstorm events remains uncertain in relation to the change in intensity and severity, as well as the possible changes in storm tracks. This indicates the importance of gaining a better understanding of possible changes in wind intensity. There is a need to start early planning as part of an adaptive management approach to manage risks to building fabric.

### 5.7 Risks and opportunities from summer and winter household energy demand (H6)

Heating demand dominates energy use in buildings at present. Climate change will reduce future heating demand, and the magnitude of this opportunity (benefit) is high in economic terms, across all future periods and scenarios, for all UK nations. The exact level of this benefit will depend on many socio-economic factors, as well as Net Zero commitments. Summer cooling demand is likely to increase with climate change, though the effect on energy demand depends upon the uptake of mechanical cooling methods (such as air conditioning), and whether the government incentivises low carbon cooling. The magnitude of this risk (economic cost of cooling to households) may be high after mid-century in England, but the risk remains low in the future for the devolved administrations. Net Zero policies will have big interactions with these risks/opportunities and present potential synergies but also potential conflicts.

Heating energy costs can make up a significant proportion of household expenditures. A household is said to be fuel poor if it needs to spend more than 10% of its income on fuel to maintain an adequate level of warmth (or cooling). Changes in household energy demand could thus have important benefits, particularly households with high energy bills. In the future, changes in household cooling demand could also have negative impacts (such as summer fuel poverty) although it is not clear how impacts would be distributed in the population.

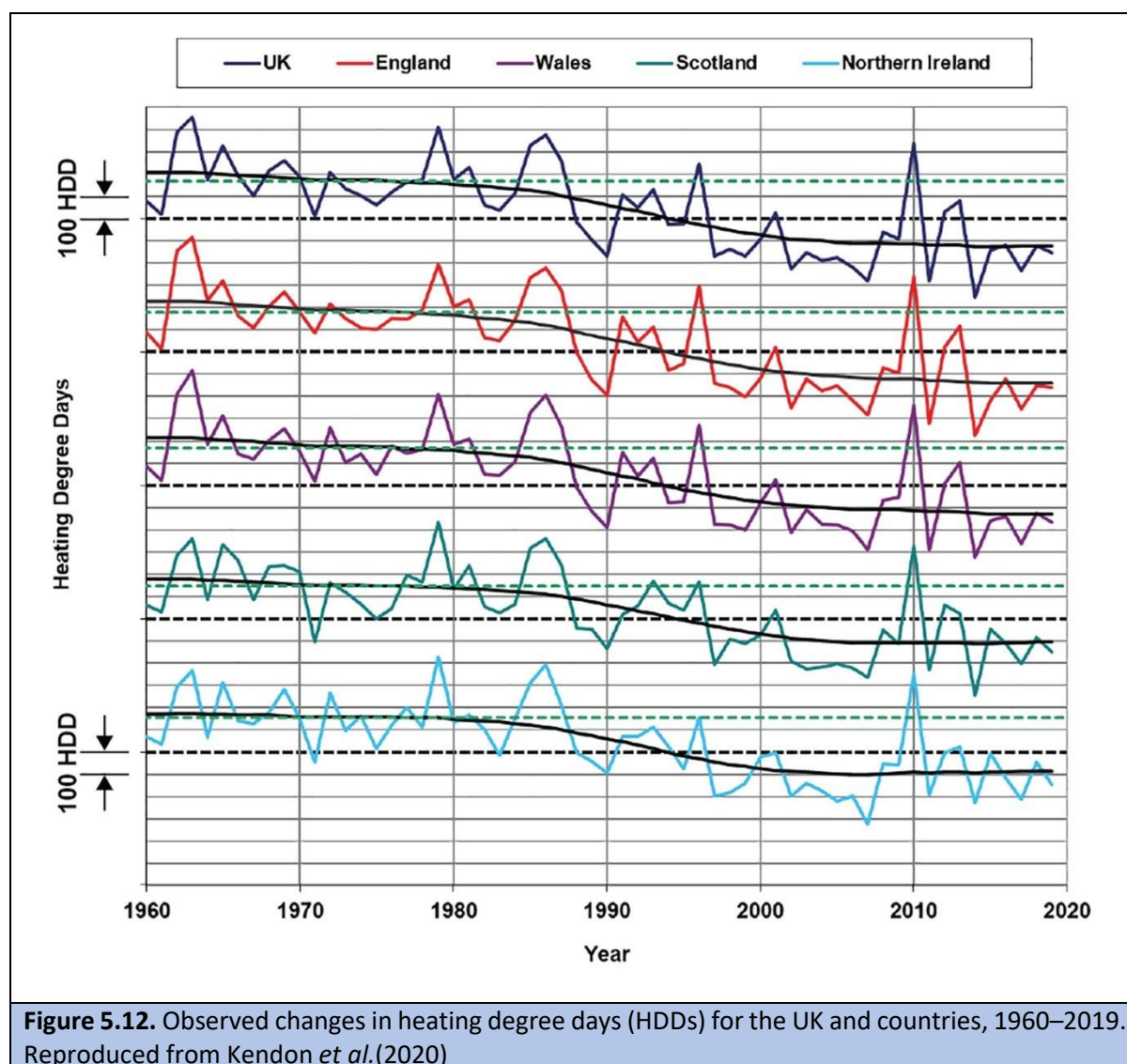
#### 5.7.1 Current and future level of risk and opportunity (H6)

This risk/opportunity has been reported at the UK level, though some quantitative information by country is available.

##### 5.7.1.1 Current and future risk - Household heating demand (H6)

Energy demand for residential buildings equated to 473 TWh in 2019 and around 65% of total domestic energy consumption is for space heating (BEIS, 2020). Current energy demand for space heating for residential buildings shows a strong relationship with temperature (Palmer and Cooper, 2013). It is often modelled in terms of heating degree days.

Consistent with observed warming trends (Chapter 1: Slingo, 2021), heating degree days (HDDs)<sup>10</sup>, in the UK have been falling in recent decades (Kendon *et al.*, 2019): the decade 2010–2019 had 4% fewer HDDs per year on average compared to 1981–2010. (Figure 5.12).



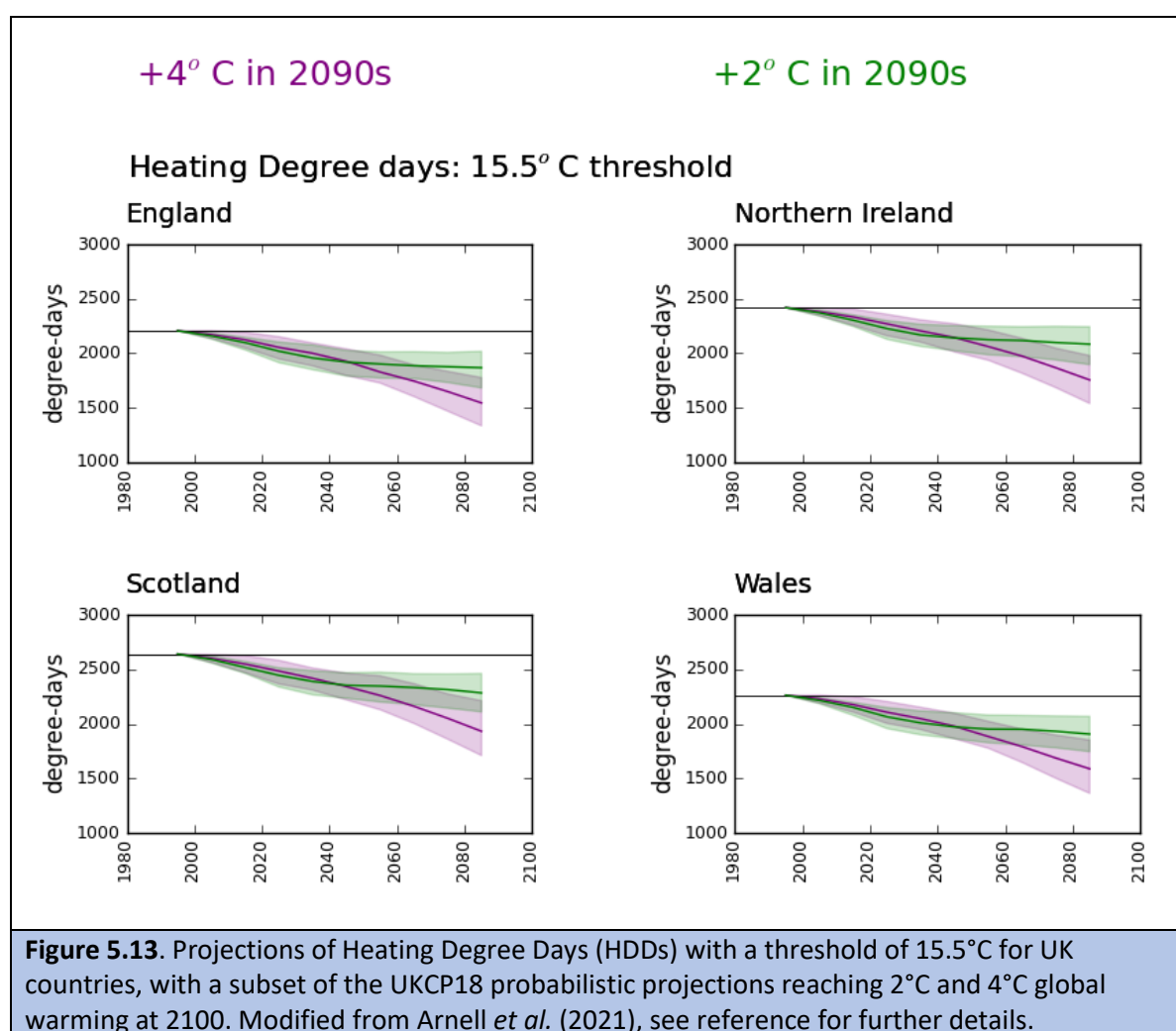
Households' demand for space heating depends not only on the temperature but also building design and insulation, heating technology, energy prices, incomes, etc. Daily variations in demand are strongly linked to temperature, but the long-term trend in actual heating demand will also have been affected by non-climatic factors such as improvements in energy efficiency improvements and insulation levels, and changes in income.

The first CCRA projected annual heating demand per household to fall significantly in the future due to climate change, across all four countries of the UK (Capon and Oakley, 2012), and more recent studies support this assessment (Arnell *et al.*, 2021; Hanlon *et al.*, 2021). HDDs are projected to

<sup>10</sup> HDD is a day-by-day sum of number of degrees by which the mean temperature is less than 15.5°C.

decrease by approximately 10% to 20% by 2071–2100 compared to 1981–2020, in a scenario of approximately 2°C global warming by 2100<sup>11</sup> (Figure 5.13). The projected decrease by 2071–2100 is approximately 20% to 40% in a scenario of 4°C global warming by 2100<sup>12</sup>.

The economic benefits of these reductions in energy demand are estimated to be significant. Capon and Oakley (2012) estimated an annual benefit of £billions/year for the 2050s for residential houses alone, using a scenario of approximately 4°C global warming by 2100<sup>13</sup>. Watkiss *et al.* (2016) estimated the reduction in winter heating costs (on average) to be +£135/ household/year by the 2050s (with a range from +£58 to +£226 for low and high scenarios and model uncertainty) compared to the 1961–1990 baseline climate. This compares to current average expenditure of around £500 to £600/household/year. Sansom (2020), using the 2050 DECC pathways tool, reported that based on a 50% probability (UKCP09 medium scenario), heating demand would be reduced by ~20% under seasonal normal conditions by 2050.



Understanding exactly how household energy demand for space heating will change in practice is complex. The baseline levels of space heating will vary with number of households and occupancy

<sup>11</sup> Subset of UKCP18 probabilistic projections reaching 2°C global warming in 2100.

<sup>12</sup> Subset of UKCP18 probabilistic projections reaching 4°C global warming in 2100.

<sup>13</sup> UKCP09 medium emissions, 50<sup>th</sup> percentile

levels, building stock, heating technology and energy efficiency, as well as energy prices and incomes. There can be a large variation in the level of benefit and cost saving under low or high price scenarios, low or high growth scenarios, and with or without Net Zero mitigation policy. Earlier mitigation policies (CCC, 2014; DECC, 2014) were estimated to reduce the costs to households of energy (from energy efficiency and thus energy savings). The implementation of Net Zero policy, however will lead to a major shift in energy efficiency, but also the energy sources and technology used to heat buildings, and thus dramatically change future baseline conditions. This is likely to lead to a shift to heat pumps and hydrogen as an alternative to gas heating, or low carbon heat networks (CCC, 2019a).

A further issue concerns the rebound effect (BEIS, 2019a). Activities that improve energy efficiency (e.g. reducing building heating demand) have the effect of reducing the overall amount of energy required (to maintain constant indoor temperature). This results in a reduction in energy bills (assuming no changes in price). The money saved can be used for heating (i.e. higher levels of comfort), or on other goods and services. This is known as the 'rebound effect'. It is stressed that there is still a large economic benefit from climate change to households, even if this may not translate through to net reductions in energy use or in emissions (due to cost savings being spent on other goods and services).

#### 5.7.1.2 Current and future risk - Household cooling demand (H6)

Currently, the use of mechanical air conditioning in residential buildings is very low, although it is increasingly common in non-domestic buildings (offices and retail premises). Abela *et al.* (2016) reported that approximately 65% of UK office space and 30% of UK retail space has air-conditioning, and that this is responsible for a significant proportion (potentially 10%) of UK electricity consumption. Approximate 3% of households have reported having air conditioners (Khare *et al.*, 2015). Cooling demand for buildings (all types, including commercial buildings) is estimated to be around 4% of electricity demand (Day *et al.*, 2009).

There has been an observed increase in cooling degree days (CDDs) (Kendon *et al.*, 2020) over recent decades, but this increase, in absolute terms, is very small compared to the reduction in HDDs. Significant peaks occur during major heatwaves.

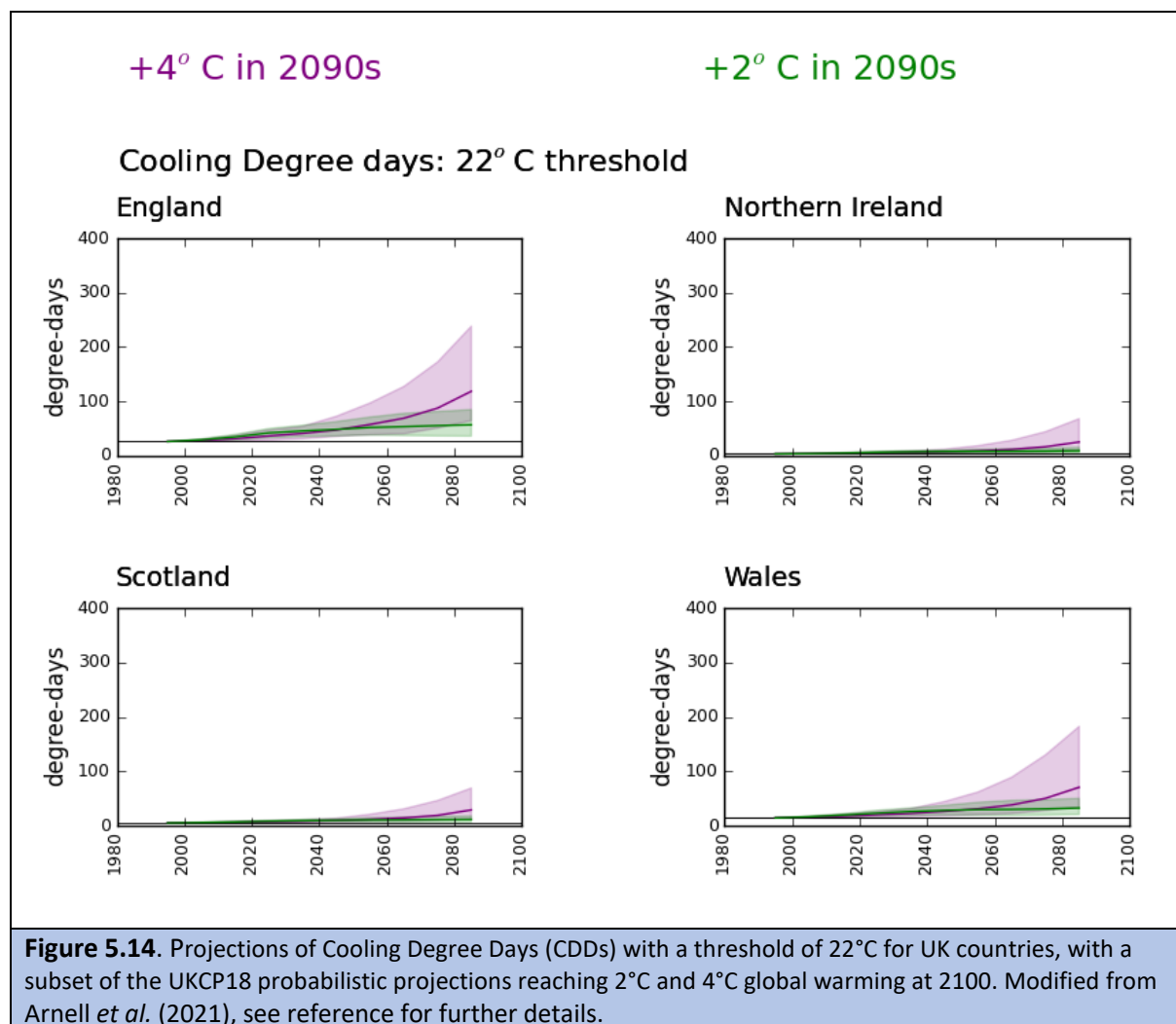
Climate change is projected to increase the number of CDDs in all countries, with greater increases with higher rates of warming (Arnell *et al.*, 2021; Hanlon *et al.*, 2021). Future changes in cooling degree days are projected to be smaller for Scotland and Northern Ireland than England and Wales for pathways to both 2°C and 4°C warming by 2100<sup>14</sup> (Figure 5.14).

Future estimates of cooling demand are complicated, as the relationship between climate and cooling demand is affected by baseline socioeconomic changes (population, housing density, housing stock, insulation levels, technology, equipment penetration level, efficiency of cooling units, behaviour, perceived comfort levels, energy prices, income, etc.) and now by Net Zero policies. Income significantly affects air conditioning penetration rates (De Cian and Sue Wing, 2019).

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<sup>14</sup> Subsets of UKCP18 probabilistic projections reaching 2°C and 4°C global warming in 2100.

Econometric analysis in other, warmer countries in Europe (Damm *et al.*, 2017) show much higher levels of air conditioning units, and energy use for cooling. However, the prevalence of air conditioning in Southern Europe is not particularly high, especially when compared to the US. Modelled estimates vary significantly on the scenario and model uncertainty range, and also on assumptions about the future uptake of air conditioning (Capon and Oakley, 2012; Damm *et al.*, 2017).



There are some studies of the impacts of climate change on future cooling demand and electricity use (for mechanical cooling) in residential buildings. Walsh *et al.* (2007) projected a strong demand increase in electricity consumption of around 10 TWh over summer months for the 2080s in a high emission scenario, due to air conditioning. This was valued indicatively in CCRA1 (Capon and Oakley, 2012). The results suggested that increases in the costs for cooling could be in the range £10–£99 million/year in 2020s, £100 million – £1 billion in the 2050s, and in excess of £1 billion in the 2080s, which are large but still much lower than the benefit in reduced costs in winter heating. The 1<sup>st</sup> NAP (Defra, 2013) reported that energy demand for domestic cooling could triple between 2010 and 2050. Sansom (2020), using the DECC 2050 Pathways and a scenario of approximately 4°C global warming by 2100<sup>15</sup>) estimated that London and the south of England in 2050 may experience CDDs

<sup>15</sup> UKCP09 medium scenario

comparable with the south of France today, and reported this would mean 5.1 million to 12.8 million households have cooling by 2050 with an associated demand ranging from 5 TWh to 13 TWh by 2050 under extreme hot weather. This would imply a high magnitude when valued using future projected energy prices (BEIS, 2019b). While the benefits from reduced winter heating occur in all regions, the changes in cooling demand with climate change are mostly projected for the South East of England.

There are also additional costs to households from purchasing air conditioning, which could be significant for the UK (Mima *et al.*, 2011). National Grid estimated that the uptake of air conditioners in the domestic sector could reach 18 million units by 2050, compared to less than one million today (National Grid, 2018). There is some evidence that individual heatwave events increase the purchase of air conditioning, which are then used more routinely at lower temperatures (Mima *et al.*, 2011).

There are some potential dis-benefits of air conditioning (AC) in buildings (see also H1) in addition to potential high energy use and costs. AC units exhaust hot air which is ejected outside, and thereby increases outdoor temperatures and can exacerbate urban heat island effects. Poor maintenance of air conditioning can lead to health problems from mould, lack of condensation drainage and circulation of airborne pollutants (WHO, 2018c).

As the UK is committed to Net Zero, the future achievement of complete decarbonisation of electricity generation entails that increased air conditioning will not be associated with significant increased greenhouse gas emissions. There is also the potential for passive alternatives to AC to reduce heating or provide cooling, and thus reduce increased summer energy demand in a Net Zero world. It is highlighted that passive systems also have costs, but these tend to be associated with up-front costs (See H1), while for mechanical cooling the highest costs are with operation. However, passive measures are less effective at cooling and air conditioning may be preferred by households, particularly under higher rates of warming (De Cian and Sue Wing, 2019). Some air conditioning units use refrigerants that have high global warming potential and therefore contribute to climate change through leakage (and irrespective of the energy source used to power them).

#### 5.7.1.3 Lock-in and thresholds (H6)

There are high risks of lock-in due to the potential for current dwellings and new buildings to be more reliant on mechanical cooling, if passive cooling and ventilation strategies are not installed, particularly for new builds and refurbishment of existing homes (see Risk H1). There are also potential lock-in issues with new buildings, and retrofit measures to existing buildings, in terms of delivering Net Zero under conditions of changing winter heating demand (i.e. systems designed to heat for the climate of today and not the future).

Under higher warming scenarios, there will be more need to consider both space heating and space cooling together in housing design, which might indicate a preference for integrated systems (for example, reverse heat pumps that provide both heating and cooling).

There are also potential thresholds for adaptation, because passive designs often have limits in their ability to reduce very high temperatures, which might indicate some path dependency with more

uptake of AC under higher warming scenarios. The same issues apply to the non-residential and industrial buildings.

#### 5.7.1.4 Implications of Net Zero (H6)

Heating demand is one of the most important areas for linkages with the UK's Net Zero targets. Net Zero will have a major influence on this opportunity/risk, because it will affect energy technology and fuel choice, household energy efficiency (e.g. building standards) and thus potential demand, as well as energy prices.

The exact influence is very complex and depends on how the Net Zero target is met. The CCC report on Net Zero (2019) highlights that near-full decarbonisation of heat for buildings is one of the biggest challenges in reducing emissions from the energy system to Net Zero by 2050 (CCC, 2019d).

The CCC report outlines the following key messages.

- In residential buildings, the parts of the stock which are generally easier and/or less costly to decarbonise include new homes, homes off the gas grid, homes suitable for district heating, and homes on the gas grid with relatively low barriers.
- The 'Further Ambition' scenario additionally deploys low-carbon heating and energy efficiency measures for homes which are considered more costly and/or difficult to decarbonise. This includes homes on the gas grid with space constraints, and homes with heritage value. This scenario also includes some conversion of residual gas demands to hydrogen.
- The analysis confirmed that reaching Net Zero emissions in buildings is achievable but that it remains costly, with a total annual cost compared to a theoretical counterfactual without any action on emissions estimated to be in the region of £15 billion in 2050.
- Delivering this will require a clear trajectory of standards. This includes delivering commitments announced under the Future Homes Standard, alongside ambitious standards for new non-residential buildings, delivering commitments on energy efficiency standards across the stock, and a long-term regulatory approach for delivering low-carbon heat.

The CCC (2019d) included a high-level assessment of the the impacts of warmer temperatures on heating and cooling demand. A much more detailed assessment has been undertaken for the 2020 Sixth Carbon budget advice. This factors in the impacts of rising temperatures on heating and cooling demand. A lower level of winter heating demand – due to climate change – should have benefits in reducing household costs related to space heating, perhaps offsetting some of the cost increases from the transition to Net Zero. However, it could also make Net Zero slightly harder to achieve, because it involves more complex consideration of designing household energy systems for a changing climate. It is much easier to design a new Net Zero energy system for a static climate than one that is changing, especially because the measures taken to improve energy efficiency have a direct influence on household overheating potential, and because if there is an increase in cooling

demand, then it changes the potential option choice for homes (i.e. from heating only to dual heating and cooling, or altering the optimal size of heat pumps).

The Sixth Carbon Budget pathways also take into account the need to look at ventilation and passive cooling alongside energy efficiency retrofit.

#### 5.7.1.5 Inequalities (H6)

Reduced heating demand has potential benefits in reducing fuel poverty, as lower income households spend a higher percentage of their total expenditure on energy, relative to the wealthiest households (Tinson *et al.*, 2016): the cost of living survey reports 9.6% of total expenditure for the former (the lowest income decile) compared to 3.6% for the latter (the highest). The benefits for households that heat their homes using electricity (currently only 7% of UK households) are higher, and critically, a large proportion of the fuel poor in England use electricity as their main source of energy. Climate change will therefore have large, positive benefits, and greater benefits for low income households due to the reductions in heating demand. It is unclear, however, whether these will lead to actual reductions in energy use, as this will depend on household behaviours (families may choose to have warmer homes, for example). Fuel poverty is also determined by many non-climate factors.

Uptake of mechanical cooling is likely to cause inequalities in the impacts of heat risks at the population level, even though the total impact on heat-related mortality is reduced. Ownership of air conditioning is strongly income dependent, and demand for electricity for cooling is likely to be more elastic than for heating (De Cian and Sue Wing, 2019). The take up of air conditioning (AC) is likely to be extremely low amongst low-income groups, and instead they will experience higher temperatures and impacts on economic welfare as temperatures increase (Lower comfort levels, and potentially higher health impacts), see Risk H1.

#### 5.7.1.6 Magnitude scores (H6)

The magnitude scores are shown below. Heating and cooling are not aggregated as the net change because they involve different systems and adaptation options.

Overall, the magnitude of the reduction in winter heating costs (a benefit) is estimated as being currently low (due to little change attributed to climate change) but this opportunity becomes high across all future periods and scenarios, for all four UK countries as the climate warms.



## 5.7.1.6.1 Winter heating (opportunity from decreases in household energy costs)

High economic savings are projected from reduced winter heating, equating to £billions in savings per year across the UK in aggregate. These findings are considered robust, i.e. high confidence, because of widespread agreement in modelling studies. The current temperature-attributable component of heating demand is considered to be high.

**Table 5.25.** Magnitude score for opportunities from winter household energy demand

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Low	High	High	High	High
	(high confidence)	(High confidence)	(high confidence)	(High confidence)	(High confidence)
Scotland	Low	High	High	High	High
	(high confidence)	(High confidence)	(high confidence)	(High confidence)	(High confidence)
Wales	Low	High	High	High	High
	(High confidence)	(High confidence)	(high confidence)	(High confidence)	(High confidence)
Northern Ireland	Low	High	High	High	High
	(High confidence)	(High confidence)	(high confidence)	(High confidence)	(High confidence)

## 5.7.1.6.2 Summer Cooling

The higher temperatures in summer with climate change will increase the need for cooling dwellings and other buildings. Household summer energy costs would increase if cooling demand is met mechanically, but there are passive and other alternatives as set out in Risk H1. This risk is assessed based on the climate-attributable proportion of summer cooling costs. There are several modelled estimates of future cooling degree days (CDDs) and these are converted to annualised energy demand. Such projections rely on unclear assumptions about future air conditioning uptake. Currently this is low. Unlike other risks, this score includes the assumption that there is significant adaptation (in the form of air conditioning uptake). The increase summer energy cost may in future years lead to a high score in England, but the exact level of increase is uncertain (Low confidence). The risk is considered lower in the devolved administrations compared to England, however, there are no good data. Because there is very little evidence to support this assumption, then all future magnitude scores are assessed as low confidence.

The current magnitude of risk is assessed as medium in England and low in other UK countries. Risks are projected to increase with increasing temperatures, particularly in the South of England in 2050s and 2080s, and for Wales under high emission scenarios in 2080s.

**Table 5.26.** Magnitude scores for risks summer household energy demand

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	High	High	High	High
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Low	Low	Low	Low	Low
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Low	Low	Low	Low	Low
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Low	Low	Low	Low	Medium
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

## 5.7.2 Extent to which the current adaptation will manage the risk and opportunity (H6)

### 5.7.2.1 Effects of current adaptation policy and commitments on current and future risks (H6)

It has not been possible to split out the assessment of adaptation by UK country for this risk and opportunity, so a UK-level analysis is presented.

Government action may be needed to realise benefits from warmer winters, such as information campaigns to raise awareness of opportunities from reduced heating costs. Additional issues for government intervention include:

- More explicit consideration of changing winter heating demand from climate change in energy strategies and policies.
- Consideration of summer cooling and winter heating in an integrated way in policies and measures.
- Addressing the barriers to synergistic policy (i.e. there are important information failures which necessitate the need for Government action).

- To ensure that energy efficiency and low carbon heating technologies being rolled out across the UK take into account future warming temperatures, as this may change the type and extent of measures needed.
- To incentivise the uptake of passive cooling over mechanical cooling measures as far as is appropriate.
- Beyond the scale of private actions, e.g. through the provision of green infrastructure and urban green spaces to reduce heat at the urban scale.

There may also be some need to consider the equity impacts of the risk and adopt appropriate policies and intervention to the way that government currently addresses fuel poverty for heating, which includes a wide range of measures (see CSE (2018)). The starting point would be to start assessing the potential risks and definitions of cooling related fuel poverty (Bridgeman *et al.*, 2018).

Air conditioning is not the only option to manage extreme heat risks (other options are described in detail in Risk H1 above) and it also has some disbenefits. The uptake of future air conditioning will be determined by a range of factors, including the affordability of upfront, operational and maintenance costs, acceptability, and perceptions regarding health benefits. The Government might intervene in the market to encourage higher standards of energy efficiency in AC or to incentivise passive options for space cooling in dwellings. For the latter, it is highlighted that there are considerable barriers to delivery, which include technical but also policy, governance and behavioural barriers (McEvoy *et al.*, 2006). In England, the Ministry of Housing, Communities and Local Government (MHCLG) published a consultation in 2021 proposing to introduce an overheating standard in new residential buildings as part of the Future Buildings Standard (MHCLG, 2021). The consultation states that overheating mitigation must be via passive cooling measures. Other policies could ensure that the costs of air conditioning and other devices better reflect current externalities associated with electricity generation, though these externalities will be reduced significantly if the electricity sector decarbonises.

In the DAs, the Welsh Government's Prosperity For All: A Low Carbon Wales (2019) sets the whole context for energy policy in Wales going forward, and does mention that the need for cooling is projected to increase and should also be considered as part of future energy demand, but does not mention falling heating degree days (Welsh Government, 2019g). The Welsh Government's reviews of Parts L and F Building Regulations (under consultation at time of writing) aim to make cooling and heating more efficient in the long term.

It has not been possible to find evidence for Scotland and Northern Ireland on the level of current and future adaptation for increased cooling demand.

#### 5.7.2.2 Adaptation Shortfall (H6)

The reduction in winter heating demand is one of the largest potential economic benefits of climate change to the UK, but the shift to Net Zero will alter the size of these opportunities. Following the discussion above, there is considered to be an adaptation shortfall over the analysis of this change (opportunity) for Net Zero policy and technology choices, and synergies and conflicts with summer over-heating (H1) and cooling demand. This is relevant for all countries.

The increase in cooling demand represents a large additional cost. As discussed above, government intervention is likely to be needed in this area, because the private sector and households alone are unlikely to be able to manage this risk and deliver Net Zero due to various barriers and constraints. Based on the CDD projections, this is most important for England.

Apart from some isolated examples, there is little information available at present on what actions are being taken by government to consider the transition to Net Zero alongside a need for increased cooling demand, and what barriers specifically need to be addressed.

### 5.7.2.3 Adaptation Scores (H6)

This opportunity (from reduced winter heating demand) is not always considered in policy, and this indicates further action is needed (to design effective policies for Net Zero). There is also no policy to address increased use of air conditioning, and to consider the risk of increasing cooling demand in synergy with changes in heating demand in a Net Zero future. This overlaps with many of the same issues presented in risk H1.

<b>Table 5.27. Adaptation scores for risks and opportunities from summer and winter household energy demand</b>			
<b>Are the risks and opportunities going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
No	No	No	No
(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)

### 5.7.3 Benefits of further adaptation action in the next five years (H6)

#### 5.7.3.1 Heating demand (H6)

A more considered analysis of this opportunity could allow potential benefits to be maxised. This is particularly important in the context of Net Zero, where changing future heating demand could have a material impact on the potential Net Zero options. This applies equally to all UK nations, as the reduction in winter heating demand is high in all areas. There is a need for better integration of this issue in Net Zero policy analysis, and subsequent government intervention to deliver Net Zero (i.e. reduced winter heating should be considered in the package of policies, incentives and instruments that government introduces to help deliver Net Zero). There is a strong economic case for such action based on the value of information, as this could significantly reduce the costs of delivering net zero for the household sector (or put another way, in a case where this information is not included, incentives will be introduced to deliver higher heating demand than is needed).

It is also highlighted that information to help households and business/industry recognise these beneficial effects, i.e. awareness raising, could help deliver the full potential economic benefits, i.e. to minimise rebound effects.

### 5.7.3.2 Cooling demand (H6)

Additional action could be undertaken to build increased cooling demand into energy policy, including through the three areas for households identified above:

- Incorporate future changes in energy demand from warmer winter and hotter summers into energy efficiency and low carbon heating policy and technologies being rolled out across the UK.
- Incentivise the uptake of passive cooling over mechanical cooling measures as far as is appropriate.
- Provide support for households that might experience 'summer fuel poverty' through e.g. inability to afford air conditioning if this is required.

Mechanical cooling has costs and benefits that can be compared to alternatives. These include a wide range of options associated with buildings (passive ventilation), behaviour, green infrastructure and land-use planning. These were set out in Risk H1. There is some information on the economics of AC versus alternatives, with analysis of the costs and benefits of many options (Grant et al., 2011; Frontier Economics *et al.*, 2013; Adaptation Sub-Committee, 2014; CCC, 2019d; Wood Plc, 2019). These studies generally favour passive cooling, but there are differences between existing building and new builds, and the timing of installation and when overheating risks occur in the future is also important (reflecting the different cost profile of capital and operating costs). At the current time, the higher externalities of air conditioning (carbon and air pollution) tend to reduce the attractiveness of this option, but this will change with decarbonisation of the electricity system under Net Zero. In a case where air conditioning is not discouraged (i.e. if choice of cooling is left to households and the private sector, and therefore met with mechanical cooling, passive or other alternatives, or cooling demand is unmet), then it would be expected that penetration rates for AC would rise significantly in England (as indicated in the evidence above). In this case, there would still be benefits from further action, notable with energy efficiency standards for cooling equipment (Low or no-regret), as well as energy efficiency awareness programmes (as there is currently for heating).

Such programmes already exist for commercial buildings, but have not yet been transferred to residential ones. In a case where passive cooling is favoured, there are a range of further actions needed, which are set out in H1.

### 5.7.3.3 Overall urgency scores (H6)

For heating demand, given the adaptation shortfall identified above, further action needed is recommended to realise the opportunities and provide the linkages to Net Zero for all UK countries.

For cooling demand, more action needed is recommended for England, further investigation for Wales, and watching brief for Northern Ireland and Scotland, though this is strongly linked to Risk H1 and the confidence is low.

Across the two areas there is a strong need for greater integration of heating and cooling issues, especially in light of Net Zero policies. The risk has been overall assessed that more action is needed in all the UK countries as the magnitude of the opportunity is high in all countries under all future scenarios, and there is a lack of policy action

<b>Table 5.28. Urgency scores for risks and opportunities from summer and winter household energy demand</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency Score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	High	Medium	Medium	Medium

#### 5.7.4 Looking Ahead (H6)

The evidence review has identified some immediate gaps, notably in attributing the effect of historic reductions in HDDs on observed heating demand trends, as well as getting better information on current residential air conditioning uptake and cooling demand. These would help in building the evidence base for future decisions.

Further research could be undertaken to understand better the implications (and costs and benefits) of climate change on heating and cooling demand for future strategies, especially for the delivery of climate resilient Net Zero policies. Research is also needed to understand household perceptions regarding heating and cooling. Policy modelling needs to include changes in demand (heating and cooling) under different climate scenarios, and for different Net Zero pathways, and consider the implications of these different energy technology choices, policy interventions, etc. This is essential given the large-scale change that will need to occur in the residential building stock over the next couple of decades – for both new and current dwellings – to deliver the Net Zero target.

As highlighted in H1, there is also a need for more investment in adaptive management approaches for managing summer cooling, which have so far received less attention in the UK in the heat domain. There are benefits from greater investment in early planning to start preparing for cooling demand changes. This is important because of the potentially large future risks and the large differences in potential action that might be needed across different pathways, i.e. for pathways to 2°C vs. 4°C global warming by 2100. There are some early examples in the literature of pathway approaches (RAMSES, 2017), including for London (Kingsborough *et al.*, 2017).

### 5.8 Risks to health and wellbeing from changes in air quality (H7)

Weather patterns can affect the formation and dispersion of air pollutants. Climate change may also change emissions of some pollutants or precursors of health-relevant pollutants. The incremental change in risk from climate change only, compared to non-climate causes, is uncertain. Air pollution emissions from combustion are falling rapidly, and are expected to decline significantly under some

(but not all) Net Zero pathways. The baseline level of pollution and interactions with climate change is likely to reduce the future risk for outdoor air quality.

Recent heatwave events have not been associated with the high levels of ground-level ozone observed in previous heatwaves, although levels of ozone were elevated. Modelling studies indicate that ground level ozone levels may decrease in the UK with climate change, but not under all climate scenarios. There is very little evidence for the impact of climate change on indoor air quality. However, household energy measures related to Net Zero have the potential to worsen indoor air quality unless specific measures are taken to avoid this.

Air quality issues have been divided into three areas based on the different policy approaches.

- Outdoor air quality associated with anthropogenic sources (including traffic, industry and agricultural sources) and wildfires
- Indoor air quality associated with housing characteristics, indoor sources and ventilation.
- Natural (non-anthropogenic) sources of air quality related to pollen and mould that affect health

### 5.8.1 Current and future level of risk (H7)

For this risk, we have been unable to provide country-specific evidence, so the risk is summarised across the UK as a whole.

#### 5.8.1.1 Current and future outdoor air quality risk (H7)

##### 5.8.1.1.1 Current risk for outdoor air quality

Outdoor air pollution is currently associated with tens of thousands of deaths per year across the UK. As such it is already a high magnitude risk for public health and government priority (PHE, 2019c). Air pollution is primarily caused by emissions of pollutants from combustion in transport and energy use, but the weather conditions can exacerbate and prolong periods of low air quality. Currently, the UK has areas with poor air quality, despite reductions in emissions and improved pollution control. Outdoor air pollution has both anthropogenic causes (transport emissions, industry, agriculture) and natural sources (dust, pollen, mould, biogenic volatile organic compounds (VOCs), and pollutants from wildfires). Emissions of VOCs from solvent use, and domestic and personal care products are becoming more important.

The main health-related hazard for the UK population is the long term (chronic impact) of particulates (PM<sub>2.5</sub> and PM<sub>10</sub>) and nitrogen oxides (NO<sub>x</sub>). Evidence for the effect of long-term exposure to NO<sub>2</sub> and mortality has increased in recent years (COMEAP, 2015). Ground level ozone also affects health (and has acute effects on mortality). There is some epidemiological evidence that short-term effects of ozone are worse on the hottest days (e.g. Pattenden *et al.* (2010)). However, evidence is limited of a significant synergistic reaction between heat and pollutant exposures.

There is relatively little detailed analysis on the meteorological drivers of air pollution episodes in the UK other than the major event in summer 2003. A study of two air pollution episodes in 2006

found that both were driven by anticyclonic conditions with light easterly and south easterly winds and high temperatures that aided pollution build up in the UK (Fenech *et al.*, 2019). Since 2011, there has been an overall decrease in the number of days of ‘moderate’ or high pollution at urban monitoring sites in England (Figure 5.15). Days with moderate or high pollution in 2018 and 2019 were associated with the prolonged hot and sunny conditions, thus, inter-annual variability in air pollution concentrations can be associated with specific meteorological conditions. Air pollution in general has declined, primarily due to the fall in NO<sub>x</sub>, but some pollutants increased in certain areas (such as ozone in cities) and others (particulates) have stayed fairly constant, with implications for health and well being.

Overall, ground level ozone levels have declined in recent decades (Diaz *et al.*, 2020). The Defra air quality report for 2018 reports that no zones in the UK were compliant with the long-term objective for ground level ozone, set for the protection of human health (i.e. the air quality standard based on the maximum daily eight-hour mean) (Defra, 2019a). The Daera assessment of ‘Air pollution in Northern Ireland’ found although the levels of most pollutants are declining, ground level ozone levels remain variable and were also high in 2018, probably due to the hot weather (Daera, 2020a).

Air quality is also affected by wildfires (see Box 5.4). The summer of 2018 was a particularly hot and dry summer which likely contributed to more favourable conditions for the outbreaks and severity of wildfires, including two major wildfires in the summer of 2018 that were declared as major incidents in the North West of England, as well as several smaller wildfires in various parts of England and a significant fire following a dry spell in the Flow Country in Scotland, in early 2019. A wildfire across Saddleworth Moor near Manchester was found to have caused poor air quality and haze over Greater Manchester. Nearby monitoring sites recorded peaks in PM<sub>2.5</sub> levels (Ffoulkes *et al.*, 2019).

#### Box 5.4. Wildfire risk to Health, Communities and Built Environment

Wildfires pose a significant risk to life, communities and the built environment, both directly and through effects on ecosystems services. In the UK, the term wildfire is officially defined as ‘*any uncontrolled vegetation fire which requires a decision, or action, regarding suppression*’ (Scottish Government, 2013). Nearly all wildfires in the UK are linked to human activities, either from land management activities or social causes that may be accidental or as arson (Gazzard *et al.*, 2016). The greatest number of fires in the UK occur in grasslands, but the largest burned areas are attained in heathlands and peatlands. The largest burned areas typically occur in National Parks, Special Areas of Conservation and Sites of Special Scientific Interest. However, the largest number of fires occur in built up areas and gardens equating to around 16,000 vegetation fires on average per year (Gazzard *et al.*, 2016).

Fire activity is mostly limited by the amount of dry vegetation susceptible to burn, and wildfires occur in two seasons in the UK; a spring peak in fires and a summer peak (Belcher *et al.*, 2021). Recent trends in wildfires in the UK indicate the last 3 years as having the largest burnt areas and the largest number of fires over the last 12 years. The percentage of days experiencing high fire weather indices (i.e. conditions conducive to the ignition and spread of fires) has been predicted to increase in both summer and spring by 2069. Up to 50% of summer days may experience high fire weather indices by 2069 assuming a 4°C global warming scenario (Belcher *et al.*, 2021).

**H1: Risks to health and wellbeing from high temperatures, and H2: Opportunities for health and wellbeing from warmer summers and winters:** There is a direct risk of injury or mortality from



fire, as well as the health effects of smoke (see Risk H7). There may also be long term impacts on mental health (Caamano-Isorna *et al.*, 2011). In good weather, use of rural and urban green space increases, and this may increase the chance of fire ignition. An enhanced social understanding of wildfire risk is required and the development of an effective communication strategy to let communities understand fire danger ratings during use of green spaces, the countryside and national parks.

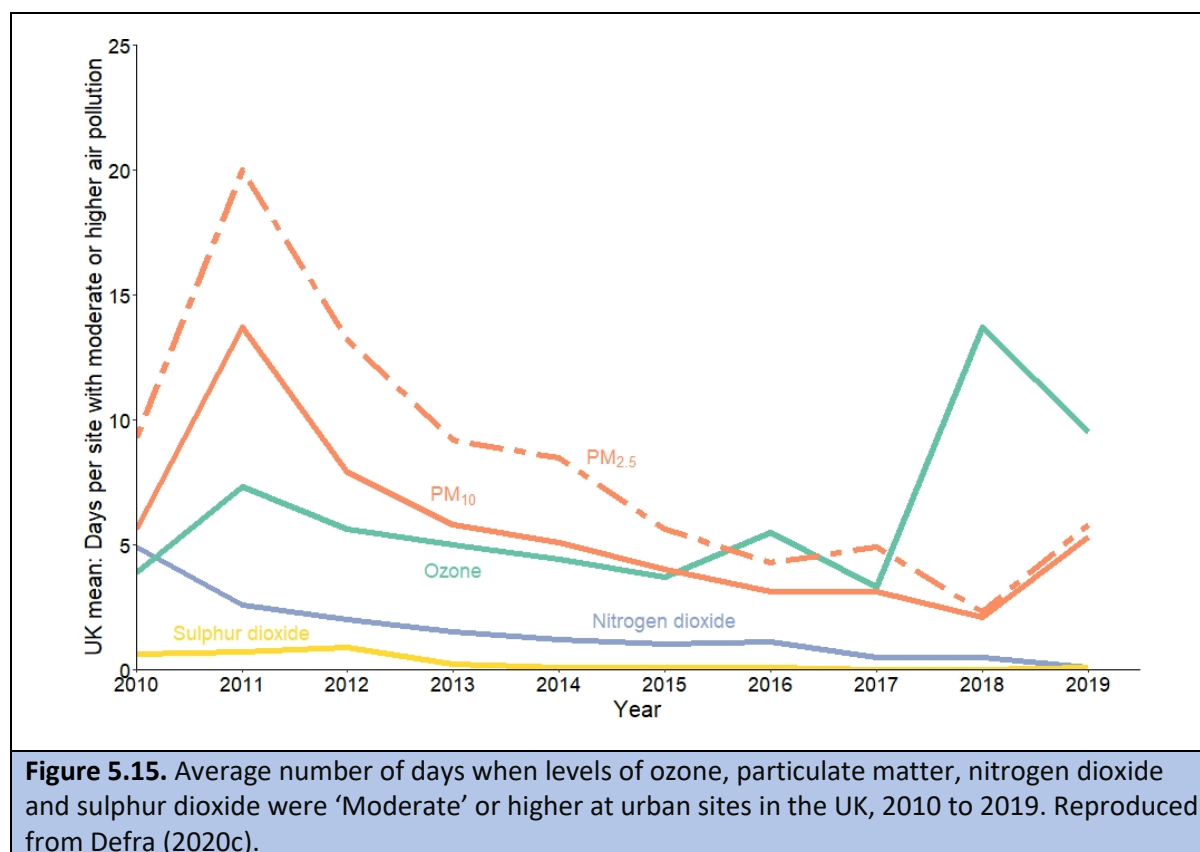
**H5: Risks to building fabric:** In fire prone countries, homes in the wildland-urban or rural-urban interface are subject to building codes for wildfire safe design (e.g. National Fire Protection Agency, USA). The enhanced fire risk due to climate change, along with the fact that the highest frequency of vegetation fires occurs in built up areas (Gazzard *et al.*, 2016), suggests that building codes in at-risk areas should include guidance for wildfire safe construction materials and features (which are distinct from structural fire codes) and have appropriate layouts for emergency assistance in terms of access and egress (e.g. NFPA, 2008). The threat of fire at the rural urban interface must be understood and regularly reviewed into the future and placed into the minds of planners and developers.

**H7: Risks to health and wellbeing from changes in air quality:** Wildfires can be a significant source of air pollution, emitting both gases and particulate matter, particularly the inhalable fractions of PM<sub>2.5</sub> and PM<sub>10</sub> (Finlay *et al.*, 2012). Wildfire smoke can affect large numbers of people. The Saddleworth Moor wildfire in 2018 exposed 4.5 million people to harmful levels of PM<sub>2.5</sub> (Graham *et al.*, 2020). There is some evidence that bacteria, fungi and other pathogens can be transported in wildfire smoke (Kobziar *et al.*, 2018; Kobziar and Thompson, 2020).

**H10: Risks to water quality and household water supplies:** Reservoirs can suffer from significant contamination if ash and organics enter them from wildfires. In the case of moorlands, peat often contains heavy metal pollution from heavy industry (Kettridge *et al.*, 2019). Therefore, where peat itself is burned, this can add heavy metal contamination to water supplies (Belcher *et al.*, 2021)

**H11: Risks to cultural heritage:** The use of fire as a land management tool is currently much debated despite its traditional use in the management of crops (e.g. stubble burning), moorlands (e.g. grouse moors) and heathlands (see Belcher *et al.* (2021)). Many communities wish to return fire or continue to use fire on the landscape which has been part of centuries-old cultural heritage. The increased risk of fires, changing fuel types and the shifting land-use anticipated (Belcher *et al.*, 2021) implies that cultural practices involving the use of fire may need to be adapted.

**Critical Infrastructure:** Three of the UKs major motorways pass through fire prone regions (M25, M6 and M60). Roads can be closed either due a fire crossing the road or burning alongside it or due to large volumes of smoke obscuring vision (Aylen *et al.*, 2015). Tailored risk assessments are required in regard to wildfire mitigation in landscapes that provide major services (e.g. water supplies), transport networks or major infrastructure.



#### 5.8.1.1.2 Future risk for outdoor air quality

Climate change will have complex regional and local effects on outdoor air pollution chemistry, transport, emissions and deposition. Climate change is very likely to affect air quality in both urban and rural areas. It directly and indirectly modifies ground-level ozone concentrations through its influence on processes determining emissions (biogenic and anthropogenic), chemistry and dispersion (see Chapter 1: Slingo, 2021). Biogenic VOCs from trees and shrubs contribute to the formation of both ozone and particulate matter, and their emission is very sensitive to temperature. Climate change will also directly and indirectly modify PM<sub>2.5</sub>/PM<sub>10</sub> and NO<sub>2</sub> concentrations. Higher temperatures during stagnation episodes (still weather) may increase peak ground level ozone. In areas with high nitrogen oxides levels, warming is likely to increase levels of ozone. Ozone is a transboundary pollutant and so large regions need to be considered for future impacts, including emissions and atmospheric chemistry beyond the boundaries of the UK.

There are few studies on health effects associated with climate change impacts alone on air quality and these estimate future exposures of outdoor ozone or particulates and the health burdens associated with these. These modelling studies generally report higher ozone-related health burdens in polluted populated regions and greater PM<sub>2.5</sub> health burdens in northern Europe (Athanasiadou *et al.*, 2010; Heal *et al.*, 2012; 2013; Doherty *et al.*, 2017). Where studies have considered both emission scenarios and climate change, the reduction in emissions is the most significant factor, specifically the large (policy-driven) reductions in emissions of ozone (O<sub>3</sub>) and PM pollutant

precursors. Under low global emission scenarios, there is also less anticipated climate change response.

There are several studies of the effects of emission scenarios and climate change together on future air quality. As emissions are a more important determinant it is often more useful to consider both factors at the same time. A review by Doherty *et al.* (2017) of climate impacts studies found that there is a lot of evidence regarding the impacts of O<sub>3</sub> on air quality in Europe although the evidence base is inconsistent. Background (average) levels of O<sub>3</sub> entering Europe is projected to decrease in most scenarios due to higher water vapour concentrations in a warmer climate. However, with the RCP8.5 scenario, higher methane (CH<sub>4</sub>) concentration is projected to lead to increases in background O<sub>3</sub> that offset the O<sub>3</sub> decrease due to climate change especially for the 2100 period.

New simulations of future air pollution have been undertaken from the CMIP6 project, using global models that incorporate both emissions and climate and which use the new SSP pathways (Turnock *et al.*, 2019; 2020). Model simulations of future ground-level ozone under several SSP pathways for Europe indicate that future ozone levels may continue rising, or they may peak in the next few years and start to fall, depending on the SSP pathway (Archibald *et al.*, 2020). Whether background ground level ozone in the UK increases or begins to decline in the future is most closely associated with the trajectory of global emissions of methane, but also the extent to which NO<sub>x</sub> emissions from industry and transport decline following policy measures (Turnock *et al.*, 2019).

Future changes in PM concentrations due to climate change remain highly uncertain. Studies indicate that particulate matter will decrease significantly by the 2050s under all climate scenarios (Lacressonnière *et al.*, 2017). However, a PM 'climate penalty' may occur due to high temperatures and humidity, and reduced precipitation in northern mid-latitude land regions in 2100. Thus, taking both emissions and climate changes into account, PM<sub>2.5</sub> is simulated to decrease but the climate penalty means that the PM<sub>2.5</sub> concentrations may not reduce in response to the emissions reduction by as much as they would have were it not for the changes in climate.

Estimates of future numbers of deaths from air pollution that are attributable to climate change have primarily been undertaken for mortality associated with high ground level ozone. In terms of future deaths from air quality that are attributable to climate change, there have been studies which model climate change impacts on air quality for Europe. These modelling studies do not model weather patterns such as blocking episodes or stagnation episodes, but use average annual temperatures. Therefore, there may be an increase in pollution episodes associated with weather patterns, even if the general trend indicates that air quality is improving. Further, if there is new evidence regarding the health impacts of long-term ozone exposures, this would have important implications for the health impacts of climate change through changes in air quality.

The impact of future climate on wildfire risks are discussed in Box 5.4 and Box 3.1 (Chapter 3: Berry and Brown, 2021). Wildfire risks may increase due to projected changes in temperature and rainfall (hot and dry weather). It is likely that the frequency of moorland fires and grassland and forest fires may increase with regional differences (Ffoulkes *et al.*, 2019). Forest fires emit particulate matter and toxic products and create extensive and long-lasting air pollution events.

#### 5.8.1.2 Current and future risk - Indoor air quality (H7)

Indoor air quality is dependent on building characteristics, ventilation, emissions from indoor sources and external air quality. Poor indoor air quality may cause or aggravate allergy and asthma symptoms, airborne respiratory infections, chronic obstructive pulmonary disease, cardiovascular disease and lung cancer (PHE, 2019a). Higher temperatures may improve or reduce indoor air quality. If temperatures are higher, then people may open windows more, which will tend to dilute pollutants of indoor origin (Taylor *et al.*, 2015a). However, in instances of poor outdoor air quality this could reduce the quality of indoor air. Extreme weather may cause windows to be closed leading to poor indoor air quality episodes. In urban areas opening windows may not be possible due to issues with security, noise and outdoor pollution (CCC, 2019a).

Indoor air quality will also be affected by the Net Zero Pathways, especially interventions that affect ventilation in buildings (see Risks H1 and H5, and the section on Net Zero below).

#### 5.8.1.3 Current and future risk - Natural (non-anthropogenic) sources of air quality (H7)

The links between climate change and allergic responses from pollen are still unclear, with the literature still being limited. It is expected that climatic factors have a role in changes to the length, start and intensity of the pollen season (D'Amato *et al.*, 2016a). Observational data collected over 30 years from the International Phenological Gardens Network indicated spring events to now be occurring six days earlier, with the most pronounced phenological changes being observed in Western Europe and Baltic regions (D'Amato *et al.*, 2016a). However, as the pollen seasons are appearing earlier in the year, often this coincides and is interrupted by late winter/early spring adverse weather conditions (D'Amato *et al.*, 2015; 2016a). Furthermore, pollen seasons are extending due to longer summer periods, delayed flowering and a lower frequency of frosts (Gezon *et al.*, 2016). A large retrospective analysis of 17 locations across the Northern Hemisphere with more than 20 years of data revealed that continued increases in temperature extremes may already be contributing to earlier, prolonged and higher seasonal pollen counts for a variety of multiple aero-allergenic pollen taxa (Ziska *et al.*, 2019).

High pollen levels cause a significant burden from allergic rhinitis. High counts of grass, nettle or tree pollen were associated with increased primary care (GP) consultations for allergic rhinitis in London (Todkill *et al.*, 2020). Evidence continues to support the association between severe asthma epidemics and thunderstorms during pollen seasons, however these are limited to periods of high atmospheric concentrations of airborne pollen (D'Amato *et al.*, 2012; 2016a). A plausible causal link between thunderstorms and asthmatic episodes in patients with pollen allergies can be made. During the first 30 minutes of thunderstorms, high rates of respirable allergen loadings are detected in the air (D'Amato *et al.*, 2012; D'Amato *et al.*, 2016b).

There is only weak evidence that air pollutants and allergenic pollen exposures interact, exacerbating allergic respiratory responses and health outcomes (Lam *et al.*, 2021). Evidence suggests both ozone and nitrogen dioxide can influence pollen morphology, altering pollen protein content and release processes and subsequently influencing the allergic reaction from inhalation (Frank and Ernst, 2016; Fleming *et al.*, 2018). These associations are species and concentration

specific. Additionally, grass pollen is able to latch onto air particulates, which increases the concentration of allergenic air pollutants (Fleming *et al.*, 2018). A study observing pollen, land cover and health outcomes reported daily grass pollen concentrations were associated with adult admissions to hospital for asthma in London after a 4–5 day lag of high pollen levels (McInnes *et al.*, 2017).

Pollen exposure may increase due to climatic influences in the geographical range of allergenic species and increased use of green spaces (Fleming *et al.*, 2018). Multiple studies using climate models have projected the range expansion of plant species such as ragweed (genus *Ambrosia*) may cause them to become established in the UK due to changes in habitat suitability by 2050 (Storkey *et al.*, 2014; Hamaoui-Laguel *et al.*, 2015). There is limited evidence on the potential for other invasive species to introduce new allergenic risks in the UK (see Chapter 3: Berry and Brown, 2021).

Allergenic responses to ragweed are projected to increase 5-fold (reference invasion scenario) in the UK due to climate change with the RCP4.5 scenario and a scenario of slow ragweed invasion (Lake, 2017). Furthermore, it is expected that the greatest proportional responses to ragweed sensitisation will be in areas of Europe which currently consider ragweed sensitisation to be uncommon (Lake *et al.*, 2017). Some projections suggest that by 2041–2060 ozone air pollution levels will decrease, which has the potential to diminish the allergenicity of ragweed pollen (Colette *et al.*, 2012). However, ragweed pollen allergenicity may rise due to increasing concentrations of atmospheric CO<sub>2</sub> and drought (El Kelish *et al.*, 2014).

Climate change effects on pollen and allergic disease are complex and there are no modelling studies that quantify future risks to health. It is not possible to assess impacts under different climate warming pathways or by UK country.

#### 5.8.1.4 Lock-in and thresholds (H7)

The lock-in risks are complex. It is not clear what the main adaptation strategies are here as outdoor air pollution is likely to reduce with more stringent emissions controls (and the new post-Brexit Air Quality Strategy).

There are lock in risks for indoor air quality as risks are determined in part by building design (see discussions on housing below).

Thresholds for wildfire risk are discussed in Chapter 3, Box 3.1 (Berry and Brown, 2021).

Air quality standards are used to manage risks from air pollution. Air quality guidelines are based on epidemiological studies, which show threshold effects on health risks for some pollutants. The guideline can also be based on the range of concentrations studied, or based on cost-benefit analysis. Some air quality guidelines are based on the lowest concentration studied in chamber studies, with it being unknown whether effects would have been found at lower concentrations. COMEAP considered the evidence on ozone thresholds in their 2015 report (COMEAP, 2015). Exceedence of air quality standards is to be avoided to prevent impacts on human health.

#### 5.8.1.5 Cross-cutting risks and interdependencies (H7)

Reduced summer rainfall and extreme summer temperatures could lead to increased risk of wildfires. High temperature and stagnation episodes also increase the risk of high levels of outdoor air pollution (from any source). There is clearly a concern that multiple environmental hazards may occur and therefore the impact on health will be more significant due to synergistic effects and possible limitations in the public health response.

The risks from wildfires are discussed in more detail in Box 5.4 and Chapter 3 (Berry and Brown, 2021).

Higher temperatures may encourage more physical activity outdoors (see risk H2) and this would include active travel. Increased cycling and walking may lead to less car use, and thus less traffic related air pollution.

#### 5.8.1.6 Implications of Net Zero (H7)

Policies to address Net Zero are likely to be the dominant factor in reducing future outdoor air pollution. Reducing greenhouse gas emissions should reduce all sources of combustion-related emissions, which are the primary source of the main air pollution-related emissions affecting health.

A preliminary 'expert' assessment of the potential impacts on UK air quality from actions to achieve Net Zero indicates that the majority of actions (once in place) are anticipated to have a net benefit on air quality, and hence a benefit on human health (AQEG, 2020). Major benefits to air quality are predicted from widespread electrification of transport and industry, where electricity supply is from 'clean' sources, and from reduced livestock in agriculture which reduces the emissions of ammonia ( $\text{NH}_3$ ) that contribute to an important fraction of  $\text{PM}_{2.5}$ . There are some actions where care is needed with respect to potential disbenefits on air quality. For example, the avoidance of high VOC-emitting species in increased forest and bioenergy crop land cover, which may lead to increased production of ozone. Some pathways to achieving Net Zero may adversely affect air quality. For example, emissions of VOCs and  $\text{NH}_3$  may increase under some agriculture/land use change, and VOCs may increase with CCS and electricity generation.

Indoor air pollution is also highly affected by Net Zero. Policies to reduce household energy emissions can reduce air change rates in properties by increasing air tightness. Many modern insulation materials also have high embodied carbon and have high off-gassing of toxic compounds. These negatively impact indoor air quality, and are further exacerbated by inadequate ventilation.

#### 5.8.1.7 Inequalities (H7)

More deprived communities are exposed to higher levels of outdoor air quality (particulates) associated with traffic sources. Poor health status, adverse health behaviours, multiple environmental exposures and psychosocial stress are more prevalent in lower socioeconomic groups (Davies, 2017). These factors may mean that pollution exposure has greater impacts on the health of these groups, a so-called 'triple jeopardy' effect (Davies, 2017). The evidence for links between

deprivation and poor air quality is stronger for NO<sub>2</sub> than for PM<sub>2.5</sub>, because NO<sub>2</sub> is higher close to roads where deprived households are more likely to be located. Further, modelling indicates that despite overall improvements in air quality, these inequalities in exposure remained until 2050 (Williams *et al.*, 2018).

The prevalence of allergic rhinitis does not show a social gradient but pollution may exacerbate allergic symptoms in some conditions.

Households on low incomes have the worst housing quality. A recent scoping review (Ferguson *et al.*, 2020) found that households with low socio-economic status generally experience poor indoor quality (with the exception of radon exposure levels).

#### 5.8.1.8 Magnitude scores (H7)

<b>Table 5.29. Magnitude scores for risks to health and wellbeing from changes in air quality</b>					
<b>Country</b>	<b>Present Day</b>  <i>(impact of climate and emissions)</i>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>  <i>(impact of climate only)</i>	<b>On a pathway to 4°C global warming at end of century</b>  <i>(impact of climate only)</i>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>  <i>(impact of climate only)</i>	<b>On a pathway to 4°C global warming at end of century</b>  <i>(impact of climate only)</i>
<b>England</b>	High  (High confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Scotland</b>	High  (High confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Wales</b>	High  (High confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Northern Ireland</b>	High  (High confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)

Scoring this future risk is difficult as the magnitude of outdoor air pollution impacts on health, wellbeing and health costs is very high. However, the role of climate hazards per se is rather small and uncertain. Present-day risks are scored from both climatic and non-climatic factors, and are therefore scored as high magnitude due to the high number of annual deaths attributed to outdoor

air pollutants. There is high confidence in this estimate and the underlying epidemiology. There is very little evidence regarding the direct impact of climate change on future indoor air quality.

Future impacts of outdoor air pollution are determined by future emissions and future climate change, but the effect of future emissions is by far the most significant factor. There is potential for air pollution to increase under some future pathways (relating to emissions, Net Zero, and climate change). Therefore, we have scored the risks as low confidence due to the high level of uncertainty (this uncertainty relates to which future pathways occur rather than the scientific uncertainty).

The future level of risk is assessed in terms of increases in pollution-attributable deaths due to climate change, as this is the only measure of impact available. Several studies for the UK and Europe indicate an increase in ozone-attributable deaths and hospitalizations.

## 5.8.2 Extent to which current adaptation will manage the risk (H7)

### 5.8.2.1 Effects of current adaptation policy and commitments on current and future risk (H7)

Current policies for addressing outdoor and indoor air quality in general are discussed by country. Managing wildfire risks are discussed in Chapter 3 (Berry and Brown, 2021) and not in this chapter. Some UK policy is national but local and regional strategies are also required to implement actions to reduce air pollution.

The UK commitment to Net Zero will make a dramatic difference to both indoor and outdoor air pollution burdens, because as it is implemented it has the potential to remove most combustion based emission sources and change the ventilation characteristics of buildings (see discussion above). This makes the assessment of adaptation benefits and shortfalls very difficult as the policy environment will be significantly different in future decades. Especially regarding indoor air quality, there needs to be an optimisation process to against adaptation and mitigation objectives, as well as health benefits and harms.

#### 5.8.2.1.1 UK-wide

The UK Clean Air Strategy (2019) sets out how air quality will be improved and monitored in the UK (Defra, 2019b). The strategy sets new targets and actions to cut public exposure to particulate matter, so that the number of people living in locations above the World Health Organisation guideline levels of  $10 \mu\text{g}/\text{m}^3$  of  $\text{PM}_{2.5}$  is reduced by 50% by 2025 relative to a 2016 baseline. Strategies for pollution reduction include Clean Air Zones and the promotion of electric vehicles. The strategy also includes action to reduce build-up of indoor air pollutants in homes and other buildings. As well as direct benefits to health, these policies protect the natural environment and cultural heritage.

The Clean Air Strategy does not consider the effects of climate change hazards (changes in temperature, humidity and rainfall) on future air quality, and does not include specific actions to



assess the incremental risk from climate change. The Clean Air Strategy focuses on reductions in emissions of air pollutants. It is likely that efforts to reduce emissions will reduce the risk from climate change for annual mean particulates (PM<sub>2.5</sub>). However, this may not be true for ground level ozone (in some circumstances), airborne pollen/moulds or air pollution caused by wildfires.

All countries in the UK undertake daily monitoring of outdoor air pollutants (including pollen) and have public health strategies for dealing with acute weather-driven episodes of poor air quality. Air pollution and socio-economic status links are important as there is the potential for inequalities as a result, which create disproportionate disease risks in more vulnerable and susceptible population groups. There is a need to enhance air pollution and health monitoring and modelling networks as well as environmental public health surveillance mechanisms to better target interventions and evaluate impacts.

The UK has enacted the EU Directives on air quality (Ambient Air Quality Directive 2008/50/EC, on Ambient Air Quality and Cleaner Air for Europe (the Air Quality Directive) and Directive 2004/107/EC (the Fourth Daughter Directive), and EU Directive 2016/2284/EU). The EU has begun infraction proceedings against the UK for failing to reduce NO<sub>2</sub> levels. Following EU-Exit, there remains uncertainty at the time of writing on future UK-wide air quality targets, and how these will be scrutinised and enforced by the Office for Environmental Protection in England, and equivalent environmental enforcement bodies in the devolved administrations.

The CMO Annual Report (2017) made several recommendations to improve air quality, including that future UK government national standards for air pollutants, developed within the next five years, should be increasingly stringent and driven by an ambition to protect human health (Davies, 2017). The report did not address the issue of climate change.

Pollen exposures are managed through health advice and public warning systems (Met Office Pollen counts). There are relatively few options to reduce pollen exposures. Land management, urban planning and tree planting activities can exacerbate or reduce allergenic exposures. Tree plantation is important to mitigate against rising concentrations of ambient pollutants leading to allergic exacerbations. Modifying the timing of grass cutting practices in the UK to be prior to flowering and the production of pollen (Fleming *et al.*, 2018) is another possibility. Further work is currently underway to model the environmental predictors of key allergenic species across the UK. This would facilitate the prediction of spatial distribution, timing of start and peak pollen exposure and concentrations of pollen grains in species under both current and future climate scenarios, and possibly facilitate better pollen forecasts (Fleming *et al.*, 2018).

In terms of biological pollutants, the management of allergenic invasive species, such as a ragweed, is the responsibility of individual landowners. Options include biological control (beetles) or insecticides (see Chapter 3: Berry and Brown, 2021). Defra issues guidance for the control of ragweed/ragwort as it is also a danger to animals (Defra, 2015b).

For England, Northern Ireland, Scotland and Wales, various strategies exist to improve air quality, though only the Welsh example looks specifically at the potential change in risk due to climate

change for outdoor or indoor air quality. Some of the main strategies and updates since CCRA2 was published are summarised briefly below.

#### 5.8.2.1.2 England

Defra and local authorities have made significant progress in developing interventions that reduce outdoor air pollution concentrations, particularly related to vehicle emissions. New policies from Defra need regulatory impact assessments that include cost-benefit analyses. The NICE guidance on air pollution has a wide range of recommendations relating to planning, development, driving, and active travel (NICE, 2017).

- The Environment Bill (at the time of writing) aims to deliver key parts of the Clean Air Strategy and introduces a duty to set a legally-binding targets for fine particulate matter concentrations, and a duty to set a long-term air quality target.
- According to the NAP2 updates provided to the CCC as part of their progress reporting (available on the CCC website), Cleaner Air is one of Public Health England's (PHE's) top ten strategic priorities, as set out in PHE's Strategy 2020–2025. PHE is developing a five-year programme of work which aims to reduce the sources of air pollution and people's exposure to it, particularly for the most vulnerable groups.
- Indoor air quality is gaining increased recognition as part of the building approval and assessment process, e.g. the BRE Home Quality Mark includes indoor pollutants, and there is the intention to include it in building standards but these are not in place as yet. NICE has issued new updated guidance on indoor air quality with specific recommendations (NICE, 2020). The CCC have also stated that there is a need for an integrated approach to addressing energy efficiency, ventilation and overheating in buildings. In ultra-energy efficient homes, mechanical ventilation may be required to ensure adequate levels of indoor air quality, and this will become more important during episodes of hot weather. However, steps must be taken to improve the design, commission, and installation of these systems, with further research into how challenges in maintaining and operating them can be overcome. Indicators to measure instances of poor indoor air quality in homes are also needed. MHCLG proposed changes to Part F (ventilation) of Building Regulations in 2019–2021 for both new build homes and existing homes when undertaking work (including when installed common energy efficiency measures). The proposed changes aim to prevent homes becoming under-ventilated and less compliant with Part F as homes become more energy efficient.
- At the regional level, the London Environment Strategy sets out the aim for London to have the 'best air quality of any major world city' by 2050, going beyond the legal requirements to protect human health and minimise inequalities (GLA, 2018). The City of London has also published an air quality strategy outlining actions that will be taken to improve air quality between 2019 and 2024, although again there is no consideration of potential impacts of climate change.

#### 5.8.2.1.3 Northern Ireland

The second Northern Ireland Climate Change Adaptation Programme (Daera, 2019) includes a reference to the potential risks from the changing climate on air quality, but doesn't include specific actions to consider this further, beyond actions to improve air quality now. Northern Ireland are publishing a Clean Air Strategy Discussion Document in 2020 (Daera, 2020b).

#### 5.8.2.1.4 Scotland

The 'Cleaner Air for Scotland – The Road to a Healthier Future' (CAFS) strategy was published by the Scottish Government in November 2015 (Scottish Government, 2015a). The purpose of CAFS is to provide a national framework which sets out how the Scottish Government and its partner organisations propose to achieve further reductions in air pollution and fulfil their legal responsibilities as soon as possible. As of 2020, there is a consultation on Cleaner Air for Scotland. The second Scottish Climate Change Adaptation Programme (Scottish Government, 2019a) also includes a dedicated section on air quality, making reference to the Cleaner Air for Scotland Strategy, its review and other efforts to reduce air pollution through uptake of electric vehicles.

#### 5.8.2.1.5 Wales

Prosperity for All: A Climate Conscious Wales (2019) includes an action to 'ensure climate change risk is considered in future policy development to improve air quality in Wales'. The main mechanism for this is the Welsh Government-published *The Clean Air Plan for Wales: Healthy Air, Healthy Wales*. The Plan sets out a 10-year pathway to achieving cleaner air (Welsh Government, 2020a) with consideration of long-term timescales and particular references to climate risk. Areas of interest to this risk include:

- Improving biodiversity and ecosystem health through nature based solutions to enhance resilience to air pollution and climate change impact.
- Use of a climate mapping model to identify pollution exceedences.
- Research currently underway to assess how housing design, materials and use affect levels of indoor air pollution, and consideration of mitigation measures.

At time of writing, a review of Building Regulations part F (ventilation) is also underway in Wales. The future risk of overheating and potential impacts on air quality are being considered.

#### 5.8.2.2 Adaptation shortfall (H7)

Current and future exposures to air pollutants are primarily dominated by factors other than climate or weather. According to the CCRA3 methods, the risk is deemed to be managed if the incremental risk that is being driven by climate change will be managed down to a low magnitude in all future likely scenarios. However, air pollution is not being well managed (based on the current high burden to human health).

The possible change in risk from climate change is not yet factored into most air quality policy documents across the UK, with the exception of Wales where there is some consideration. There

may be a gap in policies that seek to understand how the influence of climate change on future air pollution episodes might be managed.

Proposed changes to Building regulations in England for indoor air quality have not yet been brought into policy. It is not known if similar regulations will be introduced in the Devolved Administrations. Even if regulation is improved, the UK Government's 'Ventilation and indoor air quality in new homes' paper has shown a large proportion of homes simply do not comply with the current building regulations' requirements, and poor indoor air quality has been observed in several sample homes tested (MHCLG, 2019e). Achieving very high levels of thermal efficiency in new homes requires increased airtightness and the use of Mechanical Ventilation and Heat Recovery (MVHR) systems. MVHR technology has significant potential to improve air quality in homes, when properly designed, commissioned, installed, maintained and operated. However, there is also evidence that this is not always the case in current installations (CCC, 2019a). A range of studies have found cases of poor environmental conditions in houses with MVHR due to issues such as poor design and commissioning, and lack of education around use. As a result, inadequate ventilation can then exacerbate health risks due to poor air quality.

Therefore, given the gaps in assessing the effects of changing climate hazards on air quality, there is a shortfall in planning for future ground level ozone, pollen, indoor air quality, and air pollution caused by wildfire, as these hazards may increase significantly in some areas and at some times in the future depending on emissions trajectory. The policies in place to address all these risks in the present day could be improved to better address risks in the future. Our assessment therefore is that there is a partial adaptation shortfall.

#### 5.8.2.3 Adaptation Scores (H7)

<b>Table 5.30. Adaptation sources for risks to health and wellbeing from changes in air quality</b>			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially	Partially	Partially	Partially
(High confidence)	(High confidence)	(High confidence)	(High confidence)

#### 5.8.3 Benefits of further adaptation action in the next five years (H7)

The main actions that will have benefits in the next five years are further implementation of the Clean Air Strategy and uptake of the recommendations by the Chief Medical Officer. Any actions that reduce emissions of outdoor pollutants (and pollutant pre-cursors) will generally also have a positive effect on future air quality.

Further research is required on the implications of climate change for wildfire and pollen risks. Further research is needed on the interactions between air pollutants and heat exposures.

For indoor air pollution, NICE recommends the following actions to regulators to improve indoor air quality, which will also have benefits for future episodes of poor indoor air quality driven by hot weather, or increased levels of damp or mould (NICE, 2020):

- Update existing ventilation standards, for example building regulations, or develop new ones for indoor air quality. Base them on current safe limits set for pollutants in residential developments. See, for example, World Health Organization guidelines on selected pollutants (WHO, 2010) and dampness and mould (WHO, 2009b), and the Public Health England indoor air quality guidelines for selected VOCs (PHE, 2019a).
- Use existing building regulation enforcement activities to improve indoor air quality. Ensure enforcement takes place within the specified timelines. See the government's Building Regulations 2010 (UK Government, 2010) and Housing health and safety rating system operating guidance, and the Planning Portal's Failure to comply with the building regulations.

It is important to consider the health co-benefits and possible trade-offs of potential adaptation actions to address the climate-driven aspects of air quality. Nature-based solutions including tree planting have been proposed to improve air quality under climate change (Seddon *et al.*, 2020). The effect of tree planting on air quality is dependent on the scenario, scale and species used, and it is unlikely to be a major intervention to improve air quality (AQEG, 2020). Air quality gains from nature-based solutions can be marginal and other actions are also needed. Additional benefits to health and wellbeing can be drawn from increased use of green spaces (Wuyts *et al.*, 2008; Osborne *et al.*, 2017; Fleming *et al.*, 2018). Promoting the planting of trees, especially in urban areas along roads has complex effects. Vegetation can simultaneously act as a very local physical barrier (and pollutant depositional sink) between source and receptor, and as an impediment to pollutant dispersal. The net effect will be highly dependent on specific local factors, and it is not possible to generalise other than to say that it is a local effect. Tree planting may also have adverse effects for the concentration of pollen and increase allergic responses (Fleming *et al.*, 2018; Scottish Government, 2020b).

#### 5.8.3.1 Indicative costs and benefits of additional adaptation (H7)

There has been detailed analysis of the costs and benefits of options for reducing outdoor air pollution, which have supported the development of national air quality standards and policies from the European Commission's Clean Air For Europe package and policies (EC, 2013) and the UK Clean Air Strategy (Defra, 2019b) with well-established methods for valuation (Defra, 2020a). It is also highlighted that these existing air quality policies will significantly reduce air pollution levels, including background levels of regional pollution from Europe (which are important for particulate and ozone levels in the UK), as well as direct emissions from sources in the UK. This means future air pollution levels should be much lower than current, and the marginal effect of climate change will act on a much lower baseline (Lacressonnière *et al.*, 2017). The future levels of air pollution will fall even further with the implementation of Net Zero policies.

There may be benefits of additional adaptation (to target climate-induced changes in air quality and with regards to Net Zero drivers) which could address the most climate-sensitive pollutants. Climate change could be more explicitly considered within existing air quality policies and identified air

quality improvement measures). Potential areas where further action might be beneficial are improved early warning and response plans for extreme events, notably where there is an interaction between heat and air quality, and work on the costs and benefits of adaptation to improve indoor air quality.

### 5.8.3.2 Overall urgency Scores (H7)

The risks from air quality have been scored as further investigation for all UK countries. The level of incremental future risk from air pollution due to climate change could increase to a medium magnitude in the future, which would warrant an adaptation response. There is uncertainty over the degree to which climate change will act on some air pollutants such as wildfire-induced air pollution, pollen and the interactions with extreme heat or changing wind patterns, and further research is needed here. In addition, there is some uncertainty over the future baseline that climate change will be acting upon, as it is uncertain how far current policies will be effective in reducing air pollution. There is considerable uncertainty about the extent to which future risks from increased levels of ground level ozone will occur and need to be managed under higher levels of warming.

Finally, there is uncertainty in changes to policy for indoor air quality. More evidence is needed on the links to higher levels of warming and the adaptation options to address poor indoor air quality, particularly in the context of Net Zero policies.

**Table 5.31.** Urgency scores for risks to health and wellbeing from changes in air quality

Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further investigation	Further investigation	Further investigation	Further investigation
confidence	Medium	Medium	Medium	Medium

### 5.8.4 Looking ahead (H7)

In advance of CCRA4, research is needed to assess how changes to climate other than increasing temperatures, such as changing wind patterns and blocking episodes, could impact on air pollution levels. More research is needed on the interactions between air pollutants and heat exposures.

## 5.9 Risks to health from vector-borne disease (H8)

Climate change is projected to increase the risk of vector-borne diseases in the UK, particularly in Southern England. Hot summers have already affected transmission dynamics for vector borne disease. The mosquito vector of dengue has been found in the UK for the first time. Lyme disease cases may increase with climate change due to an extended transmission season and increases in person-tick contact. The risk of mosquito-transmitted diseases such as chikungunya and dengue

fever is likely to increase in England and Wales as temperatures rise. The risk that malaria may become established remains low. The risk of *Culex*-transmitted diseases such as West Nile Virus could increase in the UK.

Vector monitoring and disease surveillance are important strategies for addressing the risk from vector-borne diseases. Exit from the European Union may undermine actions to control vector-borne diseases through reduced access to international surveillance systems.

### 5.9.1 Current and future level of risk (H8)

Diseases transmitted by arthropod vectors (insects and ticks) are sensitive to temperature. There have been changes in observed distributions and seasonal activity of vectors since 2016.

Climate change impacts on vector-borne disease can be addressed through understandings of climate effects on the type of vectors:

- Tick borne diseases, including Lyme disease.
- *Culex*-transmitted diseases.
- Mosquitoes (*Aedes*) transmitted diseases.

Information for current and future risks for these diseases are only available at the UK-level and has not been broken down by UK country here.

#### 5.9.1.1 Current and future risks of tick-borne disease (H8)

There are about 20 species of tick that are endemic in the UK. It is the sheep, castor bean or deer tick (*Ixodes ricinus*) that are most likely to bite humans. Tick questing (waiting for a host to attach to) is climate (temperature and humidity) controlled, (Qviller *et al.*, 2014; Ostfeld and Brunner, 2015). It has to be warm enough for the tick to be active but still moist enough so they do not desiccate.

Lyme disease is present throughout the UK. Typically, about 10% of *Ixodes ricinus* ticks are carriers. More cases are reported in Scotland, followed by parts of southern and southwest England (Tulloch *et al.*, 2020). The laboratory-confirmed incidence of Lyme disease in England and Wales in 2016 was 1.95 cases per 100,000 (95%CI 1.84–2.06), whilst that identified in THIN (primary care data) was 3.06 (95%CI 2.47–3.75). The laboratory-confirmed incidence of Lyme disease in Scotland in 2016 was 3.15 cases per 100,000 (95%CI 2.70–3.65), in THIN it was 10.74 (95%CI 8.94–12.80). The laboratory-confirmed incidence of Lyme disease in Northern Ireland in 2016 was 0.21 cases per 100,000 (95%CI 0.07–0.52), in THIN it was 0.98 (95%CI 0.27–2.60) (Tulloch *et al.*, 2020). The higher incidence in Scotland may be due to higher humidity and higher rates of recreational activity. If diagnosed soon after initial infection, Lyme disease can be treated effectively in humans with antibiotics. Misdiagnosed or untreated Lyme disease can lead to chronic illness, debilitating sequelae and costs to the health service (Mac *et al.*, 2019).

The distribution of ticks has changed over time, which may have contributed to an increased number of confirmed cases of Lyme disease (ADAS, 2019). Climate change could be a cause of this change

due to milder winters and warmer temperatures leading to increased tick-human contact patterns, however non-climate drivers such as agriculture, land use, tourism and wild animal populations could be a more dominant influence on incidence and distribution. Attribution of the different drivers, including climate change, is not possible.

Tick-borne encephalitis (TBE) is a serious neurological disease. In Europe, TBE is transmitted by *Ixodes ricinus* ticks mostly in rural and forested areas of central, eastern and northern Europe. In 2019, TBE was discovered for the first time in the UK in ticks in two separate areas (Loeb, 2019; PHE, 2019d; Holding *et al.*, 2020). Two probable cases of TBE infection in humans have since been diagnosed in England (Kreusch *et al.*, 2019; PHE, 2020c). Some infections in humans are asymptomatic. There is a lack of evidence regarding the prevalence of TBE in the UK and the potential transmission dynamics, including the role of climate factors in transmission.

In the future, milder winters and higher temperatures could increase the exposure of people to ticks carrying Lyme disease or other pathogens (Medlock and Leach, 2015b). However, it may well be those indirect effects of climate on recreational activities (for example increased outdoor tourism) or other non-climate drivers (such as changes to land use and wild animal populations) that are a more important driver of transmission (PHE, 2021).

#### 5.9.1.2 Current and future risk of Malaria (H8)

The UK has anopheline mosquito species capable of transmitting malaria and did so historically (Kuhn *et al.*, 2003) with the most competent malaria transmitter being *Anopheles atroparvus*, which is widespread (Snow, 1998).

The current climate in the UK is already sufficiently warm in summer to allow uncontrolled malaria transmission, but higher temperatures would allow longer transmission seasons, as with other vector-borne diseases (Baylis, 2017). Malaria cases continue to be imported into the UK. PHE reported 1,683 cases imported into the UK in 2018 (PHE, 2018c), with the 10-year mean cases (2009-2018) of 1,589 (95% CI: 1,487-1,692). With a highly effective health service and effective treatment and control, malaria is unlikely to re-establish in the UK. Thus risk of local transmission is related to changes in the movement of people (the risk of introduction) as well as changes in temperature (Baylis, 2017).

The most recent risk assessment by ECDC (2017) found that localised events continue to occur in Europe but with no risk of forward transmission. Events were associated with either mosquito-borne transmission from an imported case (introduced malaria) or an imported infected mosquito (airport malaria). There is no evidence that climate change has contributed to these outbreaks. However, a reported outbreak of malaria in Greece in 2011 was linked to migrant workers who had been further displaced by migration following the floods in Pakistan (ECDC, 2011).



### 5.9.1.3 Current and future risk of arboviruses (H8)

Arboviruses of concern that affect humans include chikungunya, dengue and Zika viruses, and these are all transmitted by *Aedes albopictus* (Asian Tiger Mosquito) that is currently expanding its range. This vector has been responsible for outbreaks of chikungunya and some cases of dengue in continental Europe. Metelmann *et al.* (2019) show the importance of this vector in the outbreaks of dengue in China that may be potentially useful as an analogue to the UK.

This mosquito is not endemic in the UK but has spread around the world, often in the trade of used tyres, from its original SE Asia home to many tropical and more temperate parts of the world. The mosquito is spreading into northern areas of continental Europe, becoming more established (European Centre for Disease Prevention and Control (2020), Mosquito Maps). The mosquito has been discovered multiple times in Kent (Medlock *et al.*, 2017) but is not yet established in the UK. It is thought the mosquitoes were transported in a vehicle that had travelled from continental Europe.

*A. albopictus* mosquitoes appears to be able to adapt to non-tropical climates (Waldock *et al.*, 2013). Caminade *et al.* (2012) examined the role of climate control on the vector's current and future distribution in Europe and using a different modelling approach. Climate modelling indicates that southern England could be warm enough currently for establishment of the mosquito through overwintering of diapausing eggs, with several months of adult activity. Metelmann *et al.* (2019) focused on the UK and suggested the current, warmed, climate may be sufficient in small pockets, around the Thames Estuary, to currently sustain this mosquito. This area of suitability will spread in the future and within 50 years much of England and Wales may have a suitable climate. It is therefore important to ensure that all efforts are made to prevent *A. albopictus* and similar invasive disease vector mosquitoes (*Aedes aegypti*, *Aedes japonicus* and *Aedes koreicus*), currently established in Europe, from establishing in the UK (Medlock *et al.*, 2017). Overall, the future risks from arboviruses in the UK is related to the risk of invasion by *A. aegypti* and *A. albopictus* which is facilitated by the future warmer climate (Baylis, 2017).

*Culex modestus* is a competent vector of West Nile virus (WNV) and was found established in two marshland sites of the Thames Estuary (Golding *et al.*, 2012); it has since been found at other sites in SE England. It is seen as the main bridge vector between birds, humans and other animals, e.g. horses in the transmission of WNV, and human cases have been recorded in continental Europe. WNV could be introduced to the UK by migrating birds (Bessell *et al.*, 2016). WNV has not been found in the UK but a related virus (Usutu) has been recently been found in migrating birds in the UK (Folly *et al.*, 2020).

Temperature has been shown to increase vector competence of European mosquitos for West Nile Virus, and it is believed that cooler summer temperatures have so far limited the spread of the virus to Northern European countries. The risk of WNV outbreaks in the UK may thus increase with increasingly warm summers, likely due to viraemic migratory birds entering the UK from Northern and Western Europe (PHE, 2020c). Evidence of how the disease spreads has been observed in the US. There have been over 2,000 deaths from WNV in the US following the first case detected in New York state in 1999. The disease quickly spread through all remaining states and there is no prospect of eradication (Colpitts *et al.*, 2012). The HAIRS (Human Animal Infections and Risk Surveillance)

group at Public Health England consider that overall WNV impacts on the population is likely to be moderate or low due to the low prevalence, but introduction is assessed as likely or possible as the method of introduction is well understood and there are no mitigation measures. This assessment did not consider how risk may change in the future.

#### 5.9.1.4 Lock-in and thresholds (H8)

There is a major risk of lock in for vectors and pathogens. Once introduced, it is extremely difficult for a zoonotic pathogen to be eradicated, as it will become established within the population of native fauna. The pathogens can also become adapted to their new hosts. For example, the West Nile Virus was introduced into the Americas in 1999, and is now established throughout North America.

Disease transmission systems have temperature-related thresholds for sustained transmission. However, these are not often clearly described.

#### 5.9.1.5 Cross-cutting risks and interdependencies (H8)

There is an overlap with H2 as increased contact with nature, including urban parks, can increase the risk of contact with ticks.

Expanding areas of urban green and blue space as nature based solutions to other climate threats could potentially bring increased mosquito breeding grounds or tick-borne infections. Many key mosquito vector species thrive in natural wetland habitats. The creation of new wetlands to mitigate coastal and inland flooding may therefore have an impact on mosquito populations, and subsequently the risk of nuisance insects, and possibly disease transmission (Medlock and Leach, 2015a). Improvements to the design and management of wetlands can reduce mosquito densities, and are important to manage nuisance mosquitoes and control vector species in the event of a disease outbreak.

The risk of introduction of exotic vectors and pathogens is also discussed in Chapter 7 (Challinor and Benton, 2021).

#### 5.9.1.6 Inequalities (H8)

Evidence of inequalities in health burdens is only available for Lyme disease, as this is the only vector borne disease established in the UK. A recent study of reported cases in England found that Lyme disease patients generally originate from areas with higher socioeconomic status and are disproportionately located in rural areas (Tulloch *et al.*, 2019). This may reflect both exposures and differences in health seeking behaviour as Lyme Disease is under-reported in the general population.

#### 5.9.1.7 Magnitude scores (H8)

Quantified estimates of the future number of people that might be affected by these vector-borne diseases due to climate change cannot be determined. The magnitude of this risk (Table 5.32) is

therefore assessed using expert judgement of the the potential risk of outbreaks and the economic costs associated with outbreaks, both in terms of direct health costs and measures for disease control. The current magnitude scores for England, Wales and Scotland have been assessed as medium, reflecting the current burden of vector-borne disease (Lyme disease). Northern Ireland is scored a low as the prevalence of Lyme disease is relatively low.

**Table 5.32.** Magnitude scores for risks to health from vector-borne disease

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium  (High confidence)	Medium  (Low confidence)	Medium  (Low confidence)	High  (Low confidence)	High  (Low confidence)
<b>Northern Ireland</b>	Low  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Scotland</b>	Low  (High confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Wales</b>	Medium  (High confidence)	Medium  (Low confidence)	Medium  (Low confidence)	High  (Low confidence)	High  (Low confidence)

The risks from lock-in are high because once a disease or vector is established, it may not be possible to eradicate the vector or the pathogen. For example, if WNV is introduced into the UK, it will not be possible to eradicate this virus. The economic costs could be potentially very high if any of the diseases assessed above become established. There may also be indirect costs due to impacts on leisure, travel and tourism.

The risk of *Aedes albopictus* is greater in southern areas of England and Wales due to projected increases in temperature. The future scores for England and Wales have therefore been assessed as a medium risk in the 2050s moving to high risk in 2080s. Risk is likely to be lower in Scotland and Northern Ireland but could still be significant, therefore risk has been assessed as medium across all years and pathways. All future scores have been assessed as a low confidence due to the uncertainty around the risk of introduction, although the mechanisms of introduction are generally well understood.

## 5.9.2 Extent to which current adaptation will manage the risk (H8)

### 5.9.2.1 Effects of current adaptation policy and commitments on current and future risks (H8)

#### 5.9.2.1.1 UK-wide

Vector-borne disease risks are controlled through vector control methods and treatment of human cases. Surveillance of cases and monitoring of vector species is an essential part of vector-borne diseases control:

- The tick recording scheme (TRS) relies on members of the public to report and submit ticks. The ticks are not routinely screened for pathogens.
- Surveillance of endemic and invasive mosquitoes is undertaken by the relevant health agencies in each UK nation through programmes on port surveillance, surveys of used tyres and other ad hoc measures. This surveillance was able to identify the presence of *Aedes albopictus* (see above).

Exit from the European Union could undermine actions to control vector-borne diseases through reduced access to European Centres for Disease Control. At the time of writing, it not known whether the UK will have continued access to international public health surveillance systems such as those coordinated by ECDC.

The relatively low awareness of Lyme Disease and other vector-borne diseases in the UK population compared with that seen in Europe may also result in some cases going unrecognised. There are concerns that GPs and other clinicians may not recognise emerging infections leading to late diagnoses and worse outcomes for patients.

UK policy on managing emerging infections is addressed through the cross-government Human Animal Infections Risk Surveillance (HAIRS) group, which provides advice to the Chief Medical Officer's Advisory Panel on Dangerous Pathogens.

In 2021 it was announced that a new UK Health Security Agency will be set up to plan, prevent and respond to external threats to health including disease spread.

#### 5.9.2.1.2 England

Surveillance of ticks relies on a passive surveillance scheme. The UK's Tick Surveillance Scheme (TSS) began in 2005. Tick maps are produced by PHE and from the 'Big Tick Project Survey'.

Reducing the public's exposure to ticks, regular tick checking, and correct tick removal are crucial to minimizing risk. This can be managed through education and Public Health England (PHE) have developed Tick Awareness material and a Tick toolkit for local authorities and others.

Public Health England (PHE) maintains passive surveillance systems for notifiable diseases (clinicians report all cases of notifiable diseases). Public Health England has an ongoing mosquito surveillance programme which monitors 30 UK ports and airports. Since invasive mosquitoes became more widespread in France, surveillance has been conducted by PHE at motorway service stations in south

east England on the main routes from the south coast ferry ports and Eurotunnel. Following the discovery of the invasive species of mosquito, *Aedes albopictus*, in Kent, action was taken to eradicate eggs and larvae, that is, control of mosquito aquatic habitats was done by the local authority within a 300 metre radius. Enhanced surveillance continued through to early November 2016, and no adult mosquitoes or any further eggs were detected (Medlock *et al.*, 2017).

PHE is developing its capability to model and predict potential future changes in infection incidence related to climate change for some diseases.

The current invasive species strategy does not class species arriving in the UK due to climate change as invasive (Animal and Plant Health Agency, 2015). In addition, the strategy does not currently consider human health risks. The CCC (2019b) indicated that changes to disease surveillance were still insufficient to address climate-related risks in England.

#### 5.9.2.1.3 Northern Ireland

The Health Protection Service within the Northern Ireland Public Health Agency (PHA) has the lead role in protecting the population from infection and undertakes surveillance and monitoring of pathogens. It is not known what policies are in place within PHA to consider the increasing risk of vector-borne diseases with climate change. The second Northern Ireland Climate Change Adaptation Programme (Daera, 2019), reports on actions to address disease risks for plants and wildlife, but no actions are listed for human pathogens.

#### 5.9.2.1.4 Scotland

Health Protection Scotland (HPS) is the Scottish National Surveillance centre for communicable diseases. Health Protection Scotland published updated information on ticks and Lyme disease in Scotland in 2018, including guidance on prevention and treatment. There is no other strategy or plan to further investigate other vector-borne diseases in the context of climate change (CCC, 2019c). The second Scottish Climate Change Adaptation Programme (Scottish Government, 2019a) also includes a section on vector-borne diseases and Lyme Disease in particular.

#### 5.9.2.1.5 Wales

The climate related risk from vector-borne pathogens is recognised in the Welsh Government's adaptation plan, Prosperity for All: A Climate Conscious Wales (2019) (Welsh Government, 2019f). One particular action seeks to increase understanding of the risk, with continued monitoring at ports and airports, and efforts to increase understanding of the risk, particularly from Lyme disease, with healthcare professionals. The plan commits to research what other action is needed and to survey where vectors are entering Wales in the future. There is a recognition that increased use of blue / green infrastructure as nature based solutions to other climate threats could increase the problem with native vectors, and therefore there is a commitment to work on avoiding this issue, working with Natural Resources Wales and other experts. This will include putting in place effective measures for urban and peri-urban blue and green space to prevent habitats for vectors.

The Public Health Wales (PHW) Communicable Disease Surveillance Centre (CDSC) is the epidemiological investigation arm of the National Public Health Service for Wales. It aims to protect the population from infection through surveillance of infectious disease, support for outbreak investigation, provision of health intelligence and applied research. Again, it is not known how far the Centre has taken forward work to address any increased risk in vector-borne diseases from climate change. PHW has published guidance on what to do to avoid tick bites. It has also undertaken a climate change Health Impact Assessment (HIA), which includes the threat of increased vector borne pathogens. It is understood that the results of the HIA will influence improved policy in the area.

#### 5.9.2.2 Adaptation shortfall (H8)

Additional policies over and above the current agency oversight and surveillance systems are likely to represent low-cost and no regret options. For England and Wales, there may be more of a case for additional consideration of the risk from climate change in policy, surveillance and implementation, given the potential for medium magnitude effects in the future. This assessment has medium confidence.

#### 5.9.2.3 Adaptation Scores (H8)

The adaptation scores (Table 5.33) are based on the magnitude of the risk and current policies in place. All countries have public health measures in place for the surveillance and control of vector-borne diseases. However, such measures can be strengthened, particularly for England and Wales where risk is greatest.

<b>Table 5.33. Adaptation scores for risks to health from vector-borne disease</b>			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially	Partially	Partially	Partially
(Medium confidence)	(Low confidence)	(Medium confidence)	(Medium confidence)

#### 5.9.3 Benefits of further adaptation action in the next five years (H8)

Disease and vector surveillance is a public good. There would be direct benefits to improve disease and vector surveillance in all four countries, given the very large benefits of catching vectors and pathogens before they become established. There are benefits of further action, with many low regret options to improve or modify monitoring and surveillance systems. There are some estimates of impacts and studies of willingness to pay for vaccination against tick-borne encephalitis (Slunge, 2015). Further work on vector competence would also be beneficial. Further work on modelling risk if emergent vector borne disease due to climate change through laboratory and climate driven modelling studies is also needed.

The main benefits of further action are in enhanced monitoring and surveillance systems, including early warning, and these can be considered a low-regret option (WHO, 2013). Surveillance programs are highly cost effective. There are also studies that show that vaccination for tick-borne encephalitis (TBE) may be cost-effective, for people who may be exposed through work, rather than the whole population (Desjeux *et al.*, 2005; Slunge, 2015).

#### 5.9.3.1 Overall urgency scores (H8)

The urgency of this risk has increased as impacts on vector-borne diseases from climate change may already be occurring in the UK. More action is needed in England as the warmest parts of the UK that are more likely to experience the first introductions of novel vectors and pathogens.

<b>Table 5.34. Urgency scores for risks to health from vector-borne disease</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	Further investigation	Further investigation	Further investigation
<b>Confidence</b>	High	Low	Medium	Medium

#### 5.9.4 Looking ahead (H8)

There are a range of evidence gaps that need to be addressed to inform the next risk assessment. Improved monitoring and surveillance of vectors and pathogens would allow more detailed modelling of current and future risks. More research is also needed to map the risks to vectors and disease risks from climate and land use change.

## 5.10 Risks to food safety and food security (H9)

Climate change is likely to be an important risk for food safety in the UK. Foodborne illness has significant health and social costs. Increases in extreme weather patterns, variations in rainfall and changing annual temperatures will impact the occurrence and persistence of bacteria, viruses, parasites, harmful algae, fungi and their vectors. There has been a lack of progress to address current and future risks from climate change in food systems. Climate change may also affect food security in the UK through variability in access to food due to disruptions to the supply chain, arising from weather events and climate hazards both in the UK and abroad. The UK currently is lacking in specific policies to address the implications of climate change for food safety or food security.

This risk has two parts (food safety and food security) that will be addressed separately as policy responses are different.

## 5.10.1 Current and future level of risk (H9)

### 5.10.1.1 Current risk (H9)

There is limited evidence for each UK country for this risk, so the assessment below is UK-wide only.

#### 5.10.1.1.1 Current risk - Food Safety

Climate change is expected to be an increasingly important risk for food safety in the UK through both direct and indirect pathways. Increases in extreme weather patterns, variations in rainfall and changing annual temperatures will impact the occurrence and persistence of bacteria, viruses, parasites, harmful algae, fungi and their vectors. The risk to food safety varies by food type, as meat and eggs carry a higher risk of contamination than vegetables, for example.

**Bacterial pathogens.** Since CCRA2 there have been further epidemiological and other studies that quantify the impact of weather factors on the transmission of gastro-intestinal infections in the UK. The majority of research relates to temperature effects on *Campylobacter* and *Salmonella* cases. There is still uncertainty as to the precise mechanisms through which weather affects these diseases which make it difficult to assess the likely impact of climate change (Lake, 2017; Lake and Barker, 2018):

- *Campylobacter* is an important food-borne disease. There is reasonable evidence that the environment and weather play a role in its transmission to humans as transmission demonstrates a strong seasonality (Rushton *et al.*, 2019). Studies in other countries have confirmed this association (Rosenberg *et al.*, 2018). The association with temperature may be indirect (Djennad *et al.*, 2019). Annual FSA reporting on lab confirmed cases show that *Campylobacter* cases have not risen above a peak in reporting in 2012 and can be further supported by sampling of fresh whole UK-produced chilled chickens at retail sale (Food Standards Agency, 2020b). More recently, COVID-19 has been responsible for a drop in the reporting of foodborne disease (PHE, 2019b).
- *Salmonella* is also an important cause of foodborne infections, but its incidence is declining in the UK. There are strong positive associations between *Salmonella* cases and ambient temperature, and a clear understanding of the mechanisms behind this.

**Chemical contamination.** The chemical contaminants that are a priority for food safety standards are:

- Natural toxins (mycotoxins, marine biotoxins)
- Environmental and process contaminants (e.g. dioxins, PCBs)
- Pesticides

Food safety and quality are increasingly being assessed and climate hazards and change can have consequences for food. Chemical contamination can enter the food chain through a variety of sources, however there are concerns that heavy rainfall events may lead to increased runoff (for more detail on water quality, see Risk H10). There is currently very little evidence regarding the evidence for climate risks and chemical contamination of food.



**Food safety in fish and shellfish.** Food borne disease outbreaks and cases associated with fish and shellfish can occur due to weather patterns, pests, disease and changes to food manufacturing (GFS, 2014, 2019a). Currently shellfish and phytoplankton are monitored around the UK to track for biotoxins, *E. coli* and chemical contaminants by the Food Standards Agency (England, Northern Ireland, Wales) and Food Standards Scotland. Across the UK there have been incidences of weather-related toxin presentations in shellfish which can be harmful for human health. During a survey of Tetrodotoxin in shellfish around the UK, it was indicated that quantifiable amounts were present in shellfish from Southern England and one case in Scotland, with highest concentrations being identified in areas where sea temperature exceeded 15°C. Reports highlight that the link between sea temperature and the distribution of Tetrodotoxin in UK shellfish requires further investigation.

Additionally, shellfish-borne human *Norovirus* cases are estimated to be 21,000/year in the UK (high magnitude) with noroviruses being highly contagious, causing infectious intestinal disease and known to be very stable outside the human host whilst also being resistant to many disinfectants (Bresnan *et al.*, 2020). Importantly, a dedicated study to detect new and emerging harmful algal bloom toxins did not identify any in shellfish in UK waters (Davidson *et al.*, 2015; Turner *et al.*, 2015). In 2018, it was identified that *Vibrio* species were present in shellfish during the summer months and survey data from June to September 2018 in Southern England highlighted the presence of various human pathogenic strains (Baker-Austin *et al.*, 2018). Coincidentally, record high water temperatures were recorded during the 2018 summer which corresponded with a significant heatwave event in early June to August which may be attributable to the abundance of bacteria recorded (Bresnan *et al.*, 2020). The Food Standards Agency has developed a climate-linked vibrio prediction model to assist in strategic surveillance and assessment of changing levels of future vibrio risk (Food Standards Agency, 2020a).

**Mycotoxins.** Furthermore, the UK food system can be disrupted by mycotoxins – toxic compounds produced by types of fungus – which favour certain temperature and moisture levels (Food Standards Scotland, 2015). These toxins can contaminate food, leading to adverse health consequences such as cancers, gastrointestinal and kidney disorders and reduced resistance to infectious disease. As climate change has led to more unpredictable weather events, changing temperature and rainfall variability, the potential for fungal species to be more prevalent and more rapid proliferation of infections is a future possibility across UK. From a workshop held in Scotland which explored the role of climate change in risks from mycotoxins on the Scottish/UK food system it was concluded that even a large scale mycotoxin event in a year would not cause a major impact on the domestic market and any shortfall in supply can be mitigated by imports (Food Standards Scotland, 2015).

#### 5.10.1.1.2 Current risk - Food Security

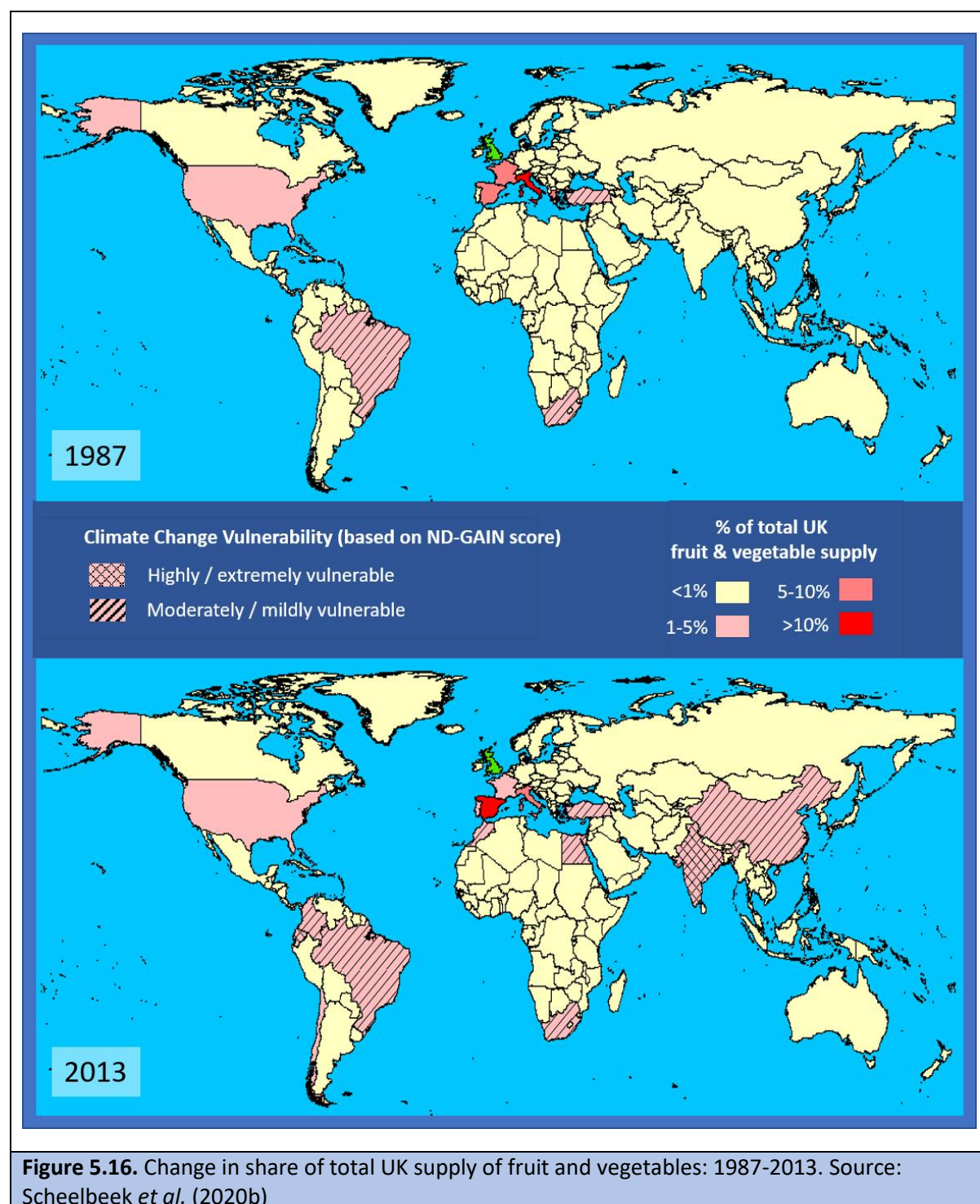
The international dimensions of food security are addressed in Chapter 7 (Challinor and Benton, 2021), but the implications for changes in imported and locally-produced food are addressed here in terms of likely impacts on public health. The UK population relies substantially on imports and a successful domestic agricultural sector (GFS, 2019b). The role of climate change in national UK

productivity and the agricultural sector is complex (Cammarano *et al.*, 2019) (discussed more widely in Risks N6 and N7 in Chapter 3: Berry and Brown, 2021).

The UK currently imports food from over 160 countries and a fifth of fresh produce is imported from countries identified as increasingly facing climate associated risks (UK Parliament, 2020). Uncertainty regarding the future viability of international agricultural supply chains due to climate change could limit UK imports and have significant impact on certain food availabilities. For specific food groups, the proportion of fruit and vegetables supplied to the UK from climate vulnerable countries has increased from 20% in 1987 to 32% in 2013 (Figure 5.16: Scheelbeek *et al.*, 2020b). The UK imports 18% of its fruit and vegetables from highly and moderately climate vulnerable countries including India, South Africa and Brazil, which has implications for future UK food security, especially with the exit from the EU (Office of Science and Technology, 2019). Extreme weather hazards can impact multiple production areas at the same time. Increasing reliance on imports from climate vulnerable countries risks availability and price and may impact the consumption of fruit and vegetables, which has significant consequences for human health (Scheelbeek *et al.*, 2020a).

Shortages in food production inevitably drive food availability and affordability, which are important determinants of health and wellbeing. Systematic reviews of food price effects have demonstrated that there is sensitivity in consumption patterns to price in relation to target groups and also benefits of interventions (subsidies, taxes) in improving diets, (e.g. Afshin *et al.*, 2017). Access to healthy and affordable food is a public health concern. The current system widely used in the UK is the 'Just-in-Time' (JiT) supply approach, which has benefits of maximising freshness and improved efficiency (UK Parliament, 2020). However, this system is vulnerable to disruption from climate impacts and shortages can occur relatively quickly (e.g. the UK experienced a climate-related vegetable shortage from Murcia, Spain in 2017, and associated prices increased by up to 300%) (see Chapter 7: Challinor and Benton, 2021).

Food shortages can compromise individual access to food and subsequently lead to poor health consequences. Evidence indicates that food insecure populations can adopt risk-adverse food purchasing, prioritising cheap foods with long-shelf lives to limit food wastage in households (The Food Foundation, 2016). Frequently, these foods are nutrient poor and highly caloric, which can increase individual risk of obesity. Furthermore, it is known that food insecurity is often associated with inadequate intake of fruit, vegetables and some essential micronutrients.



### 5.10.1.2 Future risks (H9)

#### 5.10.1.2.1 Future risk - Food Safety (H9)

There has been limited UK research on quantifying future risks to food safety from climate-related events. There are no published projections of future impacts of temperature-related diarrhoeal disease or related outcomes for the UK. The overarching assumption regarding climate change and

risks to food safety in the UK is the unpredictability of the risk with the emergence of new pathogens and threats.

There are few studies that have estimated the risk for specific health outcomes. There have been studies that project future cases of temperature-sensitive pathogens such as *Salmonella* or *Campylobacter*. For example, using a set of projections of warming slightly faster than the CCRA3 pathway to 4°C global warming by 2100<sup>16</sup>, Kuhn *et al.* (2020) project over a doubling of *Campylobacter* cases in Nordic countries by the end of the 2080s under the RCP8.5 scenario, due to higher temperatures.

Modelling studies illustrate the potential impact of increased runoff on contamination risks for shellfish. A study of 19 combined sewer overflows into coastal waters in the North West of England indicate an annual increase in spill volume and duration by 2080 (Abdellatif *et al.*, 2015). Furthermore, a substantive body of evidence largely agrees on warmer sea temperatures along the North-West European Shelf (NWS) within the end-of-century climate projections, with the projected local warming ranging between 1°C and 4°C with a scenario of approximately 4°C global warming by 2100<sup>17</sup> (Tinker and Howes, 2020). With this projected warming, there is an increased likelihood of greater abundance as well as a risk window for *Vibrio* infections to occur in the UK and NWS.

#### 5.10.1.2.2 Future risk - Food Security (H9)

Increasingly warmer temperatures have implications for longer periods of crop growth and livestock being able to be outdoors, presenting possible opportunities for the UK agricultural sector. However, the growing season is likely to be disrupted by heat stress and reduced summer precipitation, with an earlier start to the growing system exposing crops to possible frosts, e.g. fruits (Ch.3 Risk N6). Globally, imported fish yields and body size (meat yields) of marine produce are predicted to diminish with a 1-2°C global temperature increase (Baudron *et al.*, 2014; Deutsch *et al.*, 2015). Chapter 3 (Berry and Brown, 2021) and Chapter 7 (Challinor and Benton, 2021) discuss risks to marine production in more detail in Risk N14 and ID1.

Whilst the climate-linked availability of food in the UK is unlikely to be an immediate issue, it is expected that the international food system will be more vulnerable to climate shocks. As a result food price spikes may become more common in the UK as produce availability is limited, with low-probability events being more common, e.g. tropical storms and extreme heatwaves in 2019 (National Academies of Sciences Engineering Medicine, 2019). Some project a 20% mean food price rise in 2050 globally as a result of climate change, however this has a range of 0% to 60% (CCC, 2019f). A sharper rise in food prices is predicted using models with higher warming scenarios (CCC, 2019f). Importantly, changes to production of primary food produce (crops and livestock) are likely to be negatively impacted at both the 2°C and 4°C global warming scenario (Porter *et al.*, 2014).

The volatility in the global food trade can have significant health consequences, as food shortages can incur reductions in quality and safety and also introduce issues of food fraud – substitutions in

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<sup>16</sup> EURO-CORDEX regional climate models with boundary conditions from a subset of CMIP5 global climate models driven by the RCP8.5 concentration pathway.

<sup>17</sup> UKCP09 medium scenario, SRES A1B

ingredients for cheaper versions. Furthermore, much of the UK food stock is reliant upon European countries, and now that the UK has left the EU there are risks of exposure to poorer quality produce from countries with reduced governance over natural resources and less resilient supply chains (Benton *et al.*, 2020); at the time of writing, it remains unclear how big this risk is. Possible changes in the reliance on 'just-in-time' supply chains for fruit and vegetables from Europe may be expected, with potential shortages in some produce as new trade agreements are settled. Whilst COVID-19 does not represent a climate shock, it demonstrated the impact global crises can have on the UK food system. The Food Foundation published a report indicating that in the first months of the lockdown measures, adult food insecurity increased four-fold (Loopstra, 2020). The report indicates that 40% of this food insecurity was explained by a lack of food available in shops noted to be due to disruptions in the supply chain, with supermarkets experiencing acute shortages for some items.

Additional reasons for the rise in food insecurity were economic constraints and individuals being required to isolate. The COVID-19 pandemic illustrates the potential consequence of climate hazards to UK food security through increased demand, disruptions to supply chains and economic limitations.

From the current UK evidence there appears to be a potential threat to the bioavailability of micronutrients and food quality (Food Standards Agency, 2015). Globally, evidence suggests that climate change may impact the bioavailability of some micronutrients including iron and zinc, as these minerals are more susceptible to changes in plant physiology as a result of climate change (Environmental Audit Committee, 2020a) (Chapter 7: Challinor and Benton, 2021). UK food selenium concentrations may be affected by climate driven geographical shifts to more northerly farmland, where soil composition has a higher concentration of selenium. This may lead to an increase in UK dietary selenium, which has been identified as potentially protective for prostate cancer (Food Standards Agency, 2015). A potential health risk may be through a push for more localised produce, which has varied mineral soil concentrations, increasing the potential for toxicity from soil with high natural levels of copper, lead or industrial residues (Food Standards Agency, 2015).

#### 5.10.1.3 Lock-in and thresholds (H9)

Lock-in risks are not yet understood relating to food safety and security.

There are temperature thresholds associated with food safety risks, based on air temperature (*Salmonella*, *Campylobacter*) and sea surface temperatures. For example, there is a linear association between temperature and the number of reported cases of salmonellosis above a threshold of 6°C in England (with similar values seen in other European countries) (Kovats *et al.*, 2004). There are thresholds within the capacity of the food system, particularly in relation to imports and distribution systems that can get overwhelmed or disrupted.

#### 5.10.1.4 Cross-cutting risks and inter-dependencies (H9)

This risk on food security links directly to Risk ID1 'Risks to UK food availability, safety, and quality from climate change overseas', which relates to potential changes in the quality and quantity of imported food. The risk also overlaps with Risk N6 'Risks to and opportunities for agricultural and

forestry productivity from extreme events and changing climatic conditions (including temperature change, water scarcity, wildfire, flooding, coastal erosion, wind' and see Risk ID7 (Chapter 7: Challinor and Benton, 2021) looking at the risks from pathogens to agriculture and the marine environment.

#### 5.10.1.5 Implications of Net Zero (H9)

There are implications for diet and nutrition of the Net Zero pathways in the UK. Agricultural policies can reduce emissions through changing land use and dietary preferences, e.g. plant versus animal-based products (Willett *et al.*, 2019). The UK government is still in the process of developing policies to promote sustainable diets. Scotland recently published a collation of evidence regarding Scottish agriculture and achieving Net Zero by 2045 (Lampkin *et al.*, 2019).

There may be benefits or harms in terms of impacts on trade in food regarding transport options (see Chapter 7: Challinor and Benton, 2021).

#### 5.10.1.6 Inequalities (H9)

Current issues of food poverty are still prevalent in the UK, as the number of food emergency parcels distributed by Trussell Trust food banks increased from 500,000 in 2014 to more than 800,000 by 2019 (UK Parliament, 2020). With the risks of a changing climate and increasing numbers of climate shocks impacting the global food system, it is reasonable to predict possible food shortages or food price spikes which may exacerbate the issue of food poverty in the UK (UK Parliament, 2020). Food price increases have the most significant consequences for low-income families as 15% of their expenditure is allocated to food spending, compared to a 7% food expenditure by the UK's most-affluent (GFS, 2019b). To feed a future global population of 10 billion, some experts suggest dietary changes are necessary to not exceed planetary boundaries (Environmental Audit Committee, 2020a). However, it is not easy for lower socio-economic groups to afford a diet which is healthy and sustainable. A cost analysis of the UK Eatwell Guide indicated that the poorest fifth of the UK population would require spending 42% of disposable income to follow the Government recommended diet (Environmental Audit Committee, 2020a). Climate change has the ability to create or amplify inequalities regarding healthy food access in the UK, as it is known that in 2016 20% of UK residents were classified as food insecure (Loopstra *et al.*, 2019). Furthermore, due to the COVID-19 pandemic, we are moving into a period of financial uncertainty which will likely impact the most vulnerable exponentially. If future climate-related food shocks are predicted, it is likely that low-income families will be the most effected. Additionally, as the UK prepares to exit the EU, new food trade agreements will be initiated which may compromise food standards, such as antibiotic treated meat to protect against diseases. Climate risks to food systems and food insecure populations are more widely discussed in the Chapter 7 (Challinor and Benton, 2021) vulnerability case study.

## 5.10.1.7 Magnitude Scores (H9)

The social costs of poor food safety are quite high due the reported prevalence of temperature-sensitive illnesses such as campylobacteriosis and salmonellosis. Therefore even relatively small changes in incidence would entail important changes in the number of cases.

The impacts on food security are uncertain but are potentially high magnitude, as they would affect a large number of people. Further there are significant equity implications for decreased food availability.

**Table 5.35.** Magnitude scores for risks to food safety and food security

Country	Present Day (current climate risks)	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
UK	high	high	high	high	high
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

## 5.10.2 Extent to which current adaptation will manage the risk (H9)

## 5.10.2.1 Effect of current adaptation policy and commitments on current and future risk (H9)

## 5.10.2.1.1 UK wide

There are a range of adaptation measures to address food safety and security. Actions to address food security are primarily discussed in Chapter 3, Risk N7 (Berry and Brown, 2021) and Chapter 7, Risk ID1 (Challinor and Benton, 2021).

There is currently no specific policy to address climate change risks to food safety per se. This lack of adaptation was recently highlighted by the WHO which urged State health authorities to be more aware of and prepared for the specific increase in food-borne risks associated with climate change, and draft national plans (including financing and investment plans) accordingly (WHO, 2018a). Provision of scientific risk assessments can provide the evidence basis for the development and adoption of food safety standards and guidance on food safety measures, as well as to provide risk assessment on emerging food safety risks.

Current food control measures across the UK are likely to change after 1<sup>st</sup> January 2021 when the transition period following the exit from the EU has ended. At the time of writing, the post-Brexit food regulation regime for the UK was still being negotiated. EU regulatory standards are among the highest in the world and prioritise prevention of contamination over remediation. The main concern

of food safety post-EU Exit has been the importation of low quality and contaminated food products from the US (Lang and Millstone, 2019).

#### 5.10.2.1.2 England

Most of the relevant policies for England are covered under the UK section above and in Chapter 3 (Berry and Brown, 2021) and Chapter 7 (Challinor and Benton, 2021). It is also noted that the Food Standards Agency was due to update its review of climate change impacts on food safety and security published in 2015, but at the time of writing this had not yet taken place.

Defra have published part one of the National Food Strategy responding to COVID-19 and the transition period after leaving the EU. Part two of the strategy is expected to be published in the summer 2021, with a White Paper government response 6-months following.

#### 5.10.2.1.3 Northern Ireland

In addition to the UK-wide policies above (and highlighted in Chapter 3 (Berry and Brown, 2021) and Chapter 7 (Challinor and Benton, 2021)), the Going for Growth report proposes an integrated supply chain from farm to customer, but does not explicitly address critical elements of the supply chain that are upstream from regional farm production processes, such as imports of feed, fuel/energy, fertilizer and other agri-chemicals.

#### 5.10.2.1.4 Scotland

In addition to the UK-wide policies above (and highlighted in Chapter 3 (Berry and Brown, 2021) and Chapter 7 (Challinor and Benton, 2021)), across Scotland some sampling for mycotoxins is carried out by local authorities, however this is largely focussed on imports, with limited enforcement on domestic grain or retail products (Food Standards Scotland, 2015). Food Standards Scotland sets out the overall policy for the monitoring and classification of shellfish harvesting areas (Food Standards Scotland, 2017). Agencies across Scotland are currently collaborating with national and local governments, civil societies and the farming industry to prioritise sustainable food systems and protect food security at the subsequent COP26 in Glasgow, 2021.

A recent consultation for the new Good Food Nation Bill has been published which aims for a transition of food legislation to a fair, healthy and sustainable food system protecting future generations. Additionally, the published National Planning Framework 4 Position Statement highlights the potential planning policy changes which include prioritising planning for allotments and community growing spaces. Whilst these strategies are not aimed as adaptation action, they indicate ways that at the local level food availability can be more secure. However, there are issues of scale in the implementation of such strategies as they are unlikely to influence national level food security concerns.



### 5.10.2.1.5 Wales

In addition to the UK-wide policies above (and highlighted in Chapter 3 (Berry and Brown, 2021) and Chapter 7 (Challinor and Benton, 2021)), the impacts of climate change on food safety in Wales is being considered in a Climate Change Health Impact Assessment, commissioned by Public Health Wales. The outcome of the study should help inform future policy.

### 5.10.2.2 Adaptation Shortfall (H9)

The future risks of food-borne diseases in England, Wales, Scotland and Northern Ireland are currently determined to be medium-low but there is much uncertainty about future policy in the area of food safety, and the risks could grow to a high magnitude by the end of the century.

Activities such as horizon scanning are likely to be needed to understand the changing risks to food safety and security in the UK further. Food early warning systems or food risk detection systems may also play an important role in mitigating and adapting to climate change-induced food threats.

The Environmental Audit Committee (2020a) attributed increasing food poverty to the following three themes: low incomes and rising living costs; Universal Credit and the benefits system; and cuts to funding for local social care services. Climate change may affect food access (availability and price) in the UK through changes in imports of fruit and vegetables; with fluctuations in price it increasingly becomes difficult for low-income groups to afford a healthier diet (Environmental Audit Committee, 2020a).

The UK Government disagreed with the high urgency score given to food security risks in the CCRA2 Evidence Report. The Our Planet, Our Health Environmental Audit Committee report (Environmental Audit Committee, 2020b) recommended the UK Government accept the Climate Change Committee's advice from CCRA2 regarding food security risks, and indicate how best to navigate food security in a changing climate. The Committee assessed that government had failed to recognise and respond domestically, and had allowed these issues to 'fall between the cracks'.

There is a shortfall in adaptation in relation to both food access and food safety. There are likely to be emerging issues for food safety from climate change that are not adequately planned for. There are currently no explicitly additional policies that consider climate risks.

### 5.10.2.3 Adaptation Scores (H9)

<b>Table 5.36. Adaptation scores to risks to food safety and food security</b>			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially	Partially	Partially	Partially
(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

### 5.10.3 Benefits of further adaptation action in the next five years (H9)

Activities such as horizon scanning and continuous monitoring are necessary to ensure current regulations are adequate as the future to the food system is increasingly uncertain from possible emerging diseases due to climate change.

Routine monitoring of food security across the UK is also essential to protect public health and limit unnecessary costs for the health and social care system. Predicting future climate risks to the UK food system will ensure vulnerable groups to food insecurity are protected and the impacts to public health are minimised.

As mycotoxins may be an increasing risk the UK food system in the future, some proposed strategies in agriculture and food transport can limit the risk of fungal infections (e.g. optimal harvest timing). Additionally, adopting new farming techniques such as deep ploughing to control ergot (proposed in the Scottish Quality Crops Farm Assurance Guidance), targeting fungicide application, planting crop resistance varieties and introducing bio-control or genetic modification measures may limit the introduction of fungal spores to crops and the subsequent food system, though there are trade-offs with some of these measures, including deep ploughing (which can increase soil erosion and carbon losses) and increased used of pesticides (Food Standards Scotland, 2015).

#### 5.10.3.1 Indicative costs and benefits of additional adaptation (H9)

The economic impacts of food-borne disease and food safety are well understood. The FSA has developed a cost of illness model, monetising direct and indirect costs associated with food-borne illness (including food-borne *Norovirus*, *Salmonella* and *Campylobacter*). Measures to improve food safety, food regulations and education on food handling and safety, coupled with horizon scanning and continuous monitoring for emerging risks, are likely to be a low regret option (WHO, 2013). There are some economic studies that have assessed the economic benefits of maintaining or reducing food related disease cases in the UK under future climate change (e.g. Kovats *et al.* (2011)), and these find the economic benefits could be significant if the current levels of infection are maintained or increased.

For food security, there are existing actions being taken to build the resilience of food supply chains, though these have a focus on the private sector. However, the complexity of supply chains and their multi-staged processes, coupled with the uncertainty around climate change impacts, indicates that the private sector might struggle to take all appropriate actions, and there is a role for Government to play in removing some of the barriers to enable and encourage private sector adaptation, as well as ensuring a higher level of resilience along supply chains. There has been some analysis of adaptation options in this area (Watkiss *et al.*, 2019b) which has identified early low and no-regret options, but also highlighted the need for adaptive management, research and learning.

#### 5.10.3.2 Overall urgency Scores (H9)

Due to the large burden of disease associated with food safety, this risk may have significant impacts. There is also the potential for significant impacts from near term shortages in access to

healthy foods. It can be argued that further action is needed to address the impact of climate change on food security but this is highly uncertain. Due to the high levels of uncertainty, this risk is assessed for further investigation across the UK.

<b>Table 5.37. Urgency scores for risks to food safety and food security</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	Further investigation	Further investigation	Further investigation	Further investigation
<b>Confidence</b>	Medium	Medium	Medium	Medium

## 5.11 Risks to water quality and household water supply (H10)

Climate change and reduced summer precipitation resulting from climate change will increase the likelihood of periods of water scarcity and droughts, which together with demand increases from economic and population growth may lead to interruptions of household water supplies and associated health, social and economic impacts, particularly for vulnerable households. Parts of the UK, particularly within South East England, are already water stressed, and analysis of the impacts of climate change on future water supply identify that deficits are likely by the middle of the century in other parts of England and parts of Wales. Private water supplies are most vulnerable to current and future climate hazards that affect water quality (outbreaks) and quantity (interruption of supply), and are particularly important for more isolated communities. Climate change may increase the risk of contamination of drinking water through increased runoff and flooding events that overwhelm current water treatment approaches. Risks to health from contact with bathing water (sea, lakes and rivers) and harmful algal blooms may also increase with climate change.

This chapter covers a range of different pathways by which climate change may affect health and wellbeing through changes in water quality (drinking water or bathing water) and potential interruptions in household water supply. Public water supplies are discussed in detail in Chapter 4 (Risk I8: Risks to Public Water Supplies from reduced water availability: Jaroszweski, Wood and Chapman, 2021).

### 5.11.1 Current and future level of risk (H10)

There are several mechanisms by which climate hazards may affect water quality:

- Heavy downpours can increase the amount of runoff into rivers and lakes, washing sediment, nutrients, pollutants, rubbish, animal waste, and other materials into water supplies, making them unusable, unsafe, or in need of water treatment.
- High temperatures can affect concentrations of pollutants in water directly.
- High temperatures and low flows can increase concentrations of pollutants.

- Sea level rise, heavy rainfall, and coastal erosion can increase pollution from historical landfills.

With regards to potential risks for water supply resulting from water scarcity and drought, this risk focusses on risks to individuals, families and communities. Risks for water companies and related infrastructure are addressed in detail in Chapter 4 (Risk I8: Risks to Public Water Supplies from reduced water availability: Jaroszweski, Wood and Chapman, 2021).

Private water supplies are particularly at risk of contamination. Recent hot summers have highlighted that private water supplies are vulnerable to dry and warmer weather and it is likely as the climate continues to change that more private supplies will dry out (DWQR, 2018).

#### 5.11.1.1 Current risks (H10)

Evidence for some of this risk is available by UK country, particularly relating to observed effects from recent climate events (heatwaves, heavy downpours, reduced precipitation). However, the epidemiological evidence regarding the associations between meteorological factors and impacts is relevant to all UK countries.

The evidence for the effect of climate hazards for this risk relies on a range of observational studies and reported impacts of recent extreme weather events. Failures in treatment or supply are reported under current systems. The evidence is reviewed first for current risks for the range of pathways, and then evidence for future risks. For water supply, evidence for future risk is limited, as whilst the HR Wallingford research on future water availability for CCRA3 provides information on where supply deficits are likely to occur, evidence on whether these then lead to interruptions in household supply and temporary use bans is limited.

##### 5.11.1.1.1 Water Quality

There is evidence of an association between weather factors, bathing water quality and infectious intestinal disease (Eze *et al.*, 2014). A rapid evidence assessment on recreational bathing waters and gastrointestinal illness found that there is a consistent significant relationship between faecal indicator organisms and gastro-intestinal infections in freshwater, but not marine water (King *et al.*, 2015). There does not appear to have been much new research on this topic since the CCRA2 for populations in the UK.

Heavy rainfall can be a risk for water quality and has been linked to cases of human disease. With increasing extreme rainfall frequency, associated run off and storm surges, greater pressure will be exerted on sewer systems, potentially increasing virus and pathogen loads (Hassard *et al.*, 2017).

Climate hazards affect the current management of drinking water quality. Treatment failures have been reported in all UK countries associated with extreme weather events, particularly heavy rainfall. The hot summers of 2018 and 2019 were associated with failures in supply, predominantly in private water supplies (e.g. see SCCAP2, Scottish Government 2019a), but also in some piped supplies.

There is a lack of evidence regarding the impacts of reduced supplies or loss of supply on water quality.

**Box 5.5. Risks of chemical contamination from climate hazards**

Flooding and heavy rainfall can lead to the mobilization of dangerous chemicals from storage, or remobilization of chemicals already in the environment, e.g. pesticides. The UK has a considerable legacy of contaminated land related to dispersed pollution and historical landfill sites.

**H3: Risks to people, communities and buildings from flooding:** Major floods risk damaging industrial infrastructure (Chapter 4, Risk H3: Jaroszweski, Wood and Chapman, 2021) increasing the risk of a potentially harmful chemical release. Epidemiological evidence shows that chemical material may contaminate homes during flood events (Euripidou and Murray, 2004). The risk is greater when industrial or agricultural land adjoining residential land is flooded.

**H4: Risks to coastal communities from sea level rise:** Many historic landfill sites are located in low-lying coastal areas that need to be protected (Beaven *et al.*, 2020). Sea level rise or coastal erosion may expose new hazards and increase the risk of contamination of soil, water or air. The responses to climate change (adaptation or relocation) may further exacerbate the problem (Brand, 2017; Beaven *et al.*, 2018).

**H9: Risks to food safety and food security:** Chemical contamination of food can occur from increased rainfall and runoff, causing contamination of food with pesticides and other chemicals (see Risk H9 on food safety) (Boxall *et al.*, 2009).

**H10: Risks to water quality and household water supply (H10):** Climate change may lead to contamination of water by several pathways. Elevated levels of dissolved organic carbon can interfere with the effectiveness of disinfection processes and therefore increase the potential for the population to be exposed to health-damaging pollutants (see Chapter 3: Berry and Brown, 2021). Wildfires can also mobilise chemicals, and there have been examples of reservoirs contaminated by ash, organics and heavy metals from burning peat (Kettridge *et al.*, 2019).

#### 5.11.1.1.1.1 England and Wales

Climate hazards affect current drinking water quality. Treatment failures are reported due to heavy rainfall events. In 2017, there were 504 incidents in England (216 were significant and 10 were serious (Drinking Water Inspectorate (DWI)) (DWI, 2017).

Outbreaks of waterborne pathogens, such as *Cryptosporidium*, can be caused by heavy rainfall and have the potential to infect large numbers of households (DWI, 2017; 2019c). High levels of other pathogens (*E. coli*, *Enterococci* and *Clostridium perfringens*) have also been detected in water supplies following weather events (DWI, 2017). Over half of all coliforms (50/98) detected in water supplies and reservoirs during 2019 were in a period associated heavy and prolonged rainfall (DWI, 2019c).

The Drinking Water Inspectorate (DWI) indicated that adverse weather is one of the biggest risks to discolouration and interruptions of public water supplies in Wales. United Utilities was deemed the company at highest risk for failure to meet standards and has subsequently undertaken remedial measures (DWI, 2018b). The DWI suggests there is a potential link between the combination of heat, rain and potential ingress, increasing the likelihood of public supply failures (DWI, 2019c).

High temperatures also increase the risk of algal blooms in freshwater. A notable blue-green algal bloom was recorded in the Lake District in 2018 (Atkinson, 2019).

Higher temperatures may increase the risk of infectious diseases through contact with surface water. Average levels of non-viral gastrointestinal infections increased as temperature and relative humidity increased. Increasing levels of faecal indicator organisms in bathing waters were also associated with an increase in the average number of viral and non-viral gastrointestinal infections.

As of 2019 local authorities have reported a total of 37,702 and 13,880 private water supplies (PWS) in England and Wales respectively. In England, over 795,000 live or work in premises that rely on a private supply whilst this figure is 71,000 in Wales (DWI, 2019a; b). Reports indicate that 3.4% and 6.2%, respectively, of tests on English and Welsh private water supplies in 2019 failed to meet the European and national standards (DWI, 2019a). However, compared to 2010, this is a vast improvement for England, as 9.6% PWS failed European and national standards in that year (DWI, 2019a). A rural community in the South-West of England experienced loss of water and periods of insufficiency in March 2018 (DWI, 2018a). Some local residents investigated the issue and determined the cause of insufficiency to be due to a burst on an unoccupied property following a freeze-thaw event due to the 'Beast from the East'. The issue being an increased flow demand during the burst thus causing rapid drainage of the service reservoirs leading to decreases in pressure to upstream properties. Residents, consequently, operated a valve (determined non-essential during council's risk assessment) overnight to boost pressure to their properties which led to a reduction in flow to downstream properties. Eventually, the initial burst was repaired which restored supply to normal levels, however quality remained sub-optimal and the Inspectorate deemed this a risk to human health (DWI, 2018a).

#### 5.11.1.1.1.2 Northern Ireland

There is little evidence on climate factors and water-related infections or illness in Northern Ireland. No incidences have been detected relating to disruption of water quality in private water supplies from climate-related events or hazards since CCRA2. No incidences of climate-related failures of drinking water quality by public water supplies were reported from 2017 onwards.

#### 5.11.1.1.1.3 Scotland

There have been several incidences of water contamination following heavy rainfall. Water that does not meet microbiological standards (DWQR, 2017) can result in a temporary ban on drinking water, and bottled water needs to be distributed to the affected area (for example, in Orkney in 2017). Alternatively, a 'boil water' notice can be issued to consumers (DWQR, 2017).

In 2019, only 43 of 61,514 tests undertaken failed standards in Scottish treatment works (DWQR, 2019). Due to the high temperatures over the summer of 2018, there was an increase in demand for water across Scotland. This resulted in depleting reservoir levels and high-water flows, which subsequently contributed to the number of failures in manganese and iron levels. There was an increase in water quality-related incidents referencing issues of colour and odour resulting from algal presence in source waters (DWQR, 2019).

The associations with weather and bathing water quality on infectious intestinal disease have been investigated in Scotland (Eze *et al.*, 2014). Strong seasonal patterns were observed for each group of pathogens. Peak viral gastrointestinal infection was in May while that of non-viral gastrointestinal infections was in July.

#### 5.11.1.1.2 Water Supply

The UK has experienced repeated periods of low precipitation over time, with implications for public water supply, communities, vulnerable individuals and public health. The most significant recent drought was in 1976 when the public water supply was interrupted and stand-pipes were in use in places. The resilience of the water supply system can also be put under extreme pressure due to heatwaves and other reasons even if drought conditions are not reached. For example, unprecedented peak temperature periods in summer 2018, and increased household demand (as a result of COVID-19 restrictions) in May 2020 (also the driest on record) and August 2020 placed stress on water supply (Water UK, 2018; Artesia, 2020).

Analysis conducted for the updated projections of future water availability for CCRA3 (HR Wallingford, 2020) identifies an overall current supply/demand surplus of around 950 MI/day for the UK as a whole. The reduced surplus compared with CCRA2 is attributed to changes in the way water companies in England and Wales account for climate change in the 2019 Water Resource Management Plans.

The primary risk to human health from household water supply interruptions is the inability to meet demand, which would put restrictions on customers' usage. Restrictions on usage come in the form of Temporary Use Bans (TUBs) and non-essential use bans (NEUBs). Loss of household water supply would have health, social and economic impacts. However, there is limited evidence of these impacts even for the disruptions of supply experienced since 1976 (PHE, 2014). Emergency planning can be used to alleviate health and wellbeing impacts (including supplying bottled water) for vulnerable individuals who need access to plentiful water, as well as high risk individuals.

A community's ability to cope with severe droughts when standpipes need to be used is not well-researched in the UK as it still remains a rare event. Most recent experiences of the use of standpipes have been where supplies have been interrupted by flooding, extreme cold or other events. The response of water companies to these interruptions has indicated some issues regarding provision for vulnerable families (OFWAT, 2016). There is potential for conflict or social discord when access to resources are not perceived as being fair.

About 1% of the population of England and Wales use a private water supply, more in Scotland and less in Northern Ireland. Private water supplies pose more of a risk from low water quality than public supplies. Problems with private water supplies have been reported in the hot, dry summers of 2018 and 2019.

#### 5.11.1.1.2.1 England and Wales

The most significant recent drought was in 1976 when the public water supply was interrupted and stand-pipes were in use in places. Parts of the UK are already water-stressed, particularly South East England, and are facing a wide range of pressures, including population growth and increasing per capita water demand. In 2012, two dry winters caused conditions in April that were worse than any historic drought for the South and East. The situation only recovered as there was an exceptionally wet summer. The 2011–2012 drought in South East England was one of the most significant ‘near-miss’ events in recent years (Water UK, 2016). However, there has not been any formal attribution of water scarcity to climate change, although observed changes in flows and precipitation have been seen (Garner *et al.*, 2017).

Although the vast majority of water resource zones (the standard spatial unit of water supply evaluation in England and Wales) currently operate a surplus, around 16.7 million people live in water resource zones that are actually in deficit (7.89 million people in London). The South East of England is the only region with a present-day deficit.

There have not been any droughts in Wales that have had implications for household water supply since 1976, although low rainfall in spring 2020 led to the updating of drought plans in some areas, such as for the River Severn.

#### 5.11.1.1.2.2 Northern Ireland

In spring 2020, low rainfall had implications for agriculture and resulted in Northern Ireland Water Ltd. obtaining a Drought Order for abstraction, but this was not sufficiently severe to result in public water supplies to households being interrupted (Department for Infrastructure, 2020c). Less than 1% of water use in Northern Ireland comes from private water supplies (CIWEM, 2018).

#### 5.11.1.1.2.3 Scotland

Approximately 3.6% of Scottish households rely on private supplies of water, including wells for drinking water (CCC, 2019b; Scottish Government, 2019a). Private water supplies are more commonly located in rural, remote areas and managed independently from Scottish Water. The majority of private water supplies are sourced from small streams, lochs, groundwater springs and boreholes (Scottish Government, 2019a). These supplies are vulnerable to climate change due to their reliance on regular rainfall; changes in weather patterns such as increasing temperatures and changing rainfall patterns will affect the available water supply. 2018 was recorded as one of the warmest and driest years, with parts of Scotland receiving only 75% of typical annual rainfall and being exposed to excessive sunshine hours above normal levels (DWQR, 2018). This increase in temperature caused the drying up of some private water supplies across Scotland (see SCCAP2,



Scottish Government 2019a), the North East of Scotland being the worst affected as 165 supplies were reported to the Aberdeenshire council to have failed. Emergency responses resulted in bottled water being delivered to local authorities. This highlights the vulnerability of private water supplies to increasing warming and frequent heatwaves which may introduce risks to drinking water quality (private water supply interruptions discussed in risk H11) (DWQR, 2018).

The 2018 drought was marked by its severe impacts on decentralised rural water supplies, with unprecedented numbers of requests for support. The Drinking Water Quality Regulator (DWQR) reported that in summer to autumn 2018, many PWSs across the country ran dry and at least 500 of them requested emergency assistance from their respective Local Authorities (Rivington *et al.*, 2020).

#### 5.11.1.2 Future risks

##### 5.11.1.2.1 Water Quality

Future climate change and prolonged precipitation events may result in increasing levels of faecal indicator organisms in bathing waters, likely leading to increases in infectious disease.

Climate change is projected to increase the risk of harmful algal blooms (HABs) in both marine and freshwater environments (Bresnan *et al.*, 2020) (see also Chapter 3: Berry and Brown, 2021). Climate change is projected to significantly increase the amount of runoff and thereby the risk of contamination of water supplies. Climate change may significantly increase dissolved organic carbon, particularly in the winter season (Risk N4 – see Chapter 3: Berry and Brown, 2021). This has important implications for water quality as it will cost more to treat water in the future due increases in dissolved organic carbon (DOC).

In England and Wales, evidence on future water quality is limited to projections for bathing water quality. No formal risk assessments have been undertaken based on the association between pathogen transmission and rainfall.

There is no evidence of future risks specifically for Scotland and Northern Ireland.

##### 5.11.1.2.2 Water Supply

HR Wallingford (2020) assessed mid-century supply-demand balance under a central population projection with no additional adaptation for scenarios of approximately 2°C and 4°C global warming in 2070–2099<sup>18</sup>. Under these assumptions the UK faces a supply-demand balance deficit of between 650 and 920 Ml/d (equating to the daily water usage of around 4.4–6.2 million people) by the 2050s.

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<sup>18</sup> Regional climate changes from HadGEM3 60 km resolution perturbed-parameter ensemble at global warming levels of 2°C and 4°C, mapped on to pathways reaching approximately 2°C and 4°C in 2070–2099 based on 50<sup>th</sup> percentiles of UKCP18 global probabilistic projections with RCP2.6 and RCP8.5 emissions respectively. See HR Wallingford (2020) for further details.

Under a central population scenario with no additional adaptation, a deficit across the UK of between around 1,220 and 2,900 Ml/d (2°C and 4°C range) is projected by the end of the century, equating to daily water usage of around 8.3 to 19.7 million people.

#### 5.11.1.2.2.1 England and Wales

All water resource regions in England are projected to experience a deficit in supply, with the south east most likely to be affected and to be most severely affected. In the HR Wallingford (2020) scenario of approximately 4°C global warming in 2070–2099, the areas covered by the regional Water Resources South East, Water Resources North and Water Resources East groups are projected to have deficits by the 2050s with the central population projection and no additional demand-side adaptation action. Whilst reducing household consumption and leakage can substantially reduce projected deficits, their eradication may not be possible in all areas. The current and announced demand-side adaptation scenario is not sufficient to mitigate the projected impacts in Water Resources South East in the scenario of 4°C warming in 2070–2099 world, although the additional demand-side scenario would achieve this mitigation.

England's public water supply is more affected by the climate than other parts of the UK, as many more of its abstractions are already constrained by the yield of the water source, rather than other constraints such as infrastructure or licensing.

The economic loss of these restrictions on businesses and the public sector for England and Wales is £1.3 billion per day in England and Wales (Water UK, 2016).

No deficits are projected in Wales under a central population estimate, but high population growth could lead to impacts in Wales.

#### 5.11.1.2.2.2 Northern Ireland

Northern Ireland continues to maintain surpluses in public water supply in the middle and late century under a no additional adaptation scenario.

#### 5.11.1.2.2.3 Scotland

Scotland continues to maintain surpluses in public water supply in the middle and late century under a no additional adaptation / central population scenario, though deficits are possible in the high population scenario. This analysis also does not include private supplies which are more at risk. Also there are clear variations across Scotland with the west receiving far more rainfall than the east, which could lead to local deficits (Rivington *et al.*, 2020)

Commercial supplies are known as Regulated supplies and are defined in legislation. There were 3,108 Regulated supplies in Scotland in 2018; this number will increase in 2019 as rented accommodation is now classed as a Regulated Supply, but the changes have yet to feed through. Recent research conducted in Scotland identified that future levels of private water supply vulnerability will be influenced by a combination of changes in the climate that affect water

quantity, availability and interactions of the specific catchment scale water use (Rivington *et al.*, 2020). Across Scotland this will be spatially and temporally variable due to precipitation and temperature differences affecting overall water balance.

#### 5.11.1.3 Lock-in and thresholds (H10)

Key lock-in risks relate to the long term management of the water demand-supply balance across the UK, ensuring that demand and leakage elements are addressed urgently and that plans are in place to prevent future interruptions to public and private water supplies. Strategic water infrastructure, such as that required for cross-regional transfers, takes a long time to plan and organise; leaving such approaches too late could lead to implications for household water interruptions that could be avoided. Similarly, implementing transfers without sufficient long-term modelling and planning could lead the region from which water is being transferred to experience a deficit.

Water demand-supply balances for water resources zones provide a clear threshold that needs to be managed. Few studies consider the vulnerability of small rural suppliers to drought in the developed world. Sources that are sustained by precipitation, such as rainwater harvesting and some springs, and immediate aquifer recharge from rainwater (protected shallow wells and springs) are more vulnerable to precipitation variability and deficits than boreholes, but these can still be affected if aquifers are shallow and not recharged from an extensive catchment area (Rivington *et al.*, 2020). Further research is required regarding the implications for communities, particularly those who are vulnerable, regarding the length of time that TUBs are in place and the implications these could have for health and wellbeing.

#### 5.11.1.4 Cross-cutting risks and interdependencies (H10)

There are many interacting and cross-cutting (cross-chapter) issues, as water quality and quantity affect all sectors and all regions (WSP, 2020). Cross-referencing with Risk I8 in Chapter 4 (Jaroszweski, Wood and Chapman, 2021) highlights the inherent interdependency between infrastructure operation and management and the risk of household water supply interruptions.

Further research is needed on the likelihood of multiple hazards. Drought/water scarcity can manifest alongside cross-cutting issues such as heatwaves, snowstorms, floods, wildfires, and algal blooms.

The CCRA Interacting Risks project found that reduced water quality in the natural environment, leading to water supply disruptions, and sewer infrastructure flooding leading to water supply interruptions were two significant interactions that became more evident by the 2050s under 4°C warming scenarios. The indirect impact of cascading power and IT disruptions could also impact water supply infrastructure.

#### 5.11.1.5 Implications of Net Zero (H10)

Water treatment plans aim to decrease their carbon emissions. Water treatment processes can be energy intensive, therefore there is a conflict between extra treatment and meeting Net Zero targets.

The water industry was the first industrial sector in the UK and one of the first major sectors in the world to commit to a Net Zero future by 2030. The goal forms part of the industry's Public Interest Commitment (PIC) released in 2019. Around 4–5% of UK carbon emissions result from the use of water in the home (CIWEM, 2013), and if water is used more efficiently then energy and carbon is saved, as well as water achieving both mitigation and adaptation benefits. A reduction of 5% household water consumption in the UK would save approximately 1.2 MtCO<sub>2</sub>e per year.

#### 5.11.1.6 Inequalities (H10)

Private water supplies are more prevalent in remote and rural communities in Scotland and Wales. Private supplies can serve significant numbers of household in certain areas, for example, approximately 34% of the population of Argyll and Bute rely on private water supplies.

The implementation of Temporary Use Bans can have health and wellbeing impacts in terms of the loss of amenity regarding gardening and hosepipe bans and the potential for disruption to social cohesion when universal cooperation is not achieved. In other countries this has, at times, resulted in fatalities but this has not been experienced in the UK (Bryan *et al.*, 2020).

Where water supply is interrupted, it is likely that it will have the most significant impacts for vulnerable groups such as the very young, very old and those with physical and mental long-term illnesses or disabilities. As such interruptions are often accompanied by heatwaves, which also disproportionately affect at risk groups, these impacts are likely to be exacerbated (Bryan *et al.*, 2020).

#### 5.11.1.7 Magnitude scores (H10)

This risk is scored as medium for current day risks (Tables 5.38 and 5.39) because the burden on health and welfare has affected tens of thousands of people in terms of disease incidence across the UK. In the future, the risks are likely to increase if not managed better, although this is highly uncertain.

**Table 5.38.** Magnitude scores for risks to water quality for health

Country	Present Day (current climate risks)	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	Medium	Medium	medium	medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Medium	medium	medium	medium	medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Medium	Medium	Medium	medium	medium
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Medium	medium	medium	Medium	Medium
	(High confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

**Table 5.39.** Magnitude scores for risks to water supply for health

Country	Present Day (current climate risks)	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	High	High	High	High
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Low	Low	Low	Medium	Medium
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Low	Medium	Medium	Medium	Medium
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Low	Medium	Medium	Medium	Medium
	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

There is very little evidence about the effects of droughts and household water supply interruptions on human health and wellbeing. There is a large potential impact, but the evidence is limited due to uncertainties in the future climate. The risk of major drought increases in the future, with water supply deficits projected for parts of England (highest risk in the south east where current water supply is limited). A major drought leading to loss of water to thousands or hundreds of thousands of households is possible and therefore the future risk for England (2050s and 2080s, both climate futures) is assessed as being high magnitude. This risk is assessed as lower magnitude than I8, as whilst there is already a supply deficit in the South East, this is not resulting in health and wellbeing implications for people in terms of TUBs or other use restrictions. The confidence score is also rated lower than for I8 as the relationship between supply deficits and actual interruption of household water supply is not a direct correlation, as it relates to the contingency plans put in place for water companies and householders where private water supplies are used. In addition, I8 only covers public water supply, whereas this risk encompasses private water supply for which there is less evidence regarding future impacts.

### 5.11.2 Extent to which current adaptation will manage the risk (H10)

#### 5.11.2.1 Effects of current adaptation policy and commitments on current and future risks (H10)

##### 5.11.2.1.1 Water Quality

###### 5.11.2.1.1.1 UK-wide

To manage the risks of water contamination in the short-term, regulators impose a temporary ban on ingesting or drinking the water. In some cases a permanent ban on domestic use of the site is enforced (DWI, 2019d).

The Water Industry Act 1991 (the 1991 Act) sets out the legal framework for ensuring good quality drinking water supplies in England and Wales. The relevant legislation in Scotland is the Water Industry (Scotland) Act, and in Northern Ireland, the Water and Sewerage Services (Northern Ireland) Order 2006. Outbreaks linked to water supplies are investigated by local public health teams and environmental health departments, however, sporadic cases may not be detected without additional epidemiological investigation.

Private water supplies are not regulated in the same way as public supplies. Each private supply has an individual owner and local authorities can mandate owners to make changes to supplies that violate health and safety criteria.

###### 5.11.2.1.1.2 England and Wales

The Drinking Water Inspectorate is the regulator for drinking water quality in England and Wales. The second National Adaptation Programme (NAP2, Defra 2018c) includes actions related to interruption of household water supplies, but not risks to household water quality.

Prosperity for All: A Climate Conscious Wales highlighted the Welsh Government's Water Strategy for Wales, which was published in 2015, covers a 25 year period, and aims to maintain high levels of water quality and protect the health of people in Wales. The strategy identifies the risks from climate change and is underpinned by an all-Wales action plan. In addition, the Water Health Partnership for Wales is an initiative that brings together relevant agencies to work together more effectively to protect public health by ensuring the provision of safe drinking water. Agencies in the Partnership include the Drinking Water Inspectorate (DWI), Welsh Government, local authority public and environmental health, the water companies and Public Health Wales. Natural Resources Wales is the regulatory body responsible for managing water resources in Wales. They provide oversight of both Bathing and Drinking Water in Wales through a wide range of strategies and plans and regulatory activity. Water companies also report annually on bathing water quality in Wales (NRW, 2018).

#### 5.11.2.1.1.3 Northern Ireland

The second Northern Ireland Climate Change Adaptation Programme (NICCAP2, Daera 2019) highlights that some evidence has pointed to recent declines in bathing water quality in Northern Ireland, and mentions the 'System for Bathing Water Quality Monitoring' (SWIM) that will investigate and model the linkage between heavy rainfall events and poor bathing water quality. It also makes reference to The 'Sustainable Water – A Long-Term Water Strategy for Northern Ireland (2015–2040)' which recognises that all policies must factor in the future implications of climate change on both quality and quantity of water resources. It also notes that the 'Drinking Water and Health Guidance' is reviewed annually and contains action to be taken should drinking water quality fall below health based criteria. Northern Ireland's ten year 'Making Life Better' strategy for health and wellbeing has an objective to provide safe and clean drinking water.

#### 5.11.2.1.1.4 Scotland

The Drinking Water Quality Regulator for Scotland (DWQR) is responsible for ensuring that drinking water in Scotland is safe to drink. There are no specific policies about climate change and water quality, however, there are strategies in place to support households with private water supplies. The second Scottish Climate Change Adaptation Programme (SCCAP2, Scottish Government 2019a) highlights the vulnerability of Scotland's private water supplies to poor quality issues, though it does not elaborate on actions to support drinking water quality specifically.

Bathing waters sites are important assets for local, regional economies. Domestic visits alone to Scottish seaside locations generate an average of 1.5 million trips and £323 million in expenditure per annum. Bathing water quality is one of the adaptation indicators listed in SCCAP2.

#### 5.11.2.1.2 Water Supply

##### 5.11.2.1.2.1 England and Wales

Recognising the need to work together to address the supply-demand balance, organisations responsible for England's water supplies have come together to understand the long term needs of

all sectors that depend on a secure supply of water – public water supply, agriculture, power generation, industry and the environment. The recently published National Framework for Water resources (EA, 2020d), identifies strategic water needs for England and its regions across all sectors up to and beyond 2050. It also requires water companies in regional groups to revisit their planned frequencies of use for non-essential use bans in the light of the planned increase to drought resilience, recognising the benefits to customers if frequencies reduce. It states that the planned implementation of non-essential use bans should not become more frequent to achieve the reduction in the use of more extreme restrictions such as standpipes and rota cuts. It also requires water companies in regional groups to explore how they can coordinate the use of temporary use bans to provide clearer messaging to customers and improve environmental protection at times of scarcity.

Most companies state that standpipes/emergency orders are ‘unacceptable’ but in practice the worst drought experienced to date in the 1926–2016 record could only just be managed without them; they are still ‘expected’ for more severe droughts. This is complicated by the presence of emergency storage in reservoirs, which could theoretically be used to further delay the introduction of standpipes for some companies. However, the provision and use of such emergency storage is variable and many of the large systems in south and east England are managed so that standpipe-type restrictions would be implemented at the point emergency storage starts to be used (EA, 2015b).

Another strategy to manage the security of household water supplies is to reduce household demand. Defra consulted on measures to reduce personal water use (including labelling the water efficiency of appliances, metering, building standards and behaviour change) (Defra, 2019c). Domestic water consumption in England has fallen from 155 l/h/d in 2003/2004 to 141 l/h/d in 2017/2018, but consumption increases during hot summers cause significant issues for supply (Chapter 4: Jaroszweski, Wood and Chapman, 2021; and Chapter 6: Surminski, 2021). Regional water groups recently agreed to contribute to a national ambition of average per capita consumption of 110 l/p/d by 2050, and to review this ambition every five years (EA, 2020d).

#### 5.11.2.1.2.2 Northern Ireland

NI Water published a new draft Water Resources and Supply Resilience (WR &SR) Plan in 2019 (Northern Ireland Water, 2019). NI Water has made significant improvements in water resilience for customers since the last Plan was launched in 2012, which was reported as a concern in the CCRA2 Evidence Report. The draft Plan aims to build on this work, ensuring continued high levels of leakage detection, sustained investment in water mains and water efficiency initiatives.

The WR & SR Plan has taken the target Level of Service (LoS) as providing customer reliability of 97.5%, equivalent to accepting a water supply failure for one year in 40. This is in line with the LoS adopted by several other UK water companies, including both Welsh Water and Scottish Water. To maintain customer supplies in drought events more severe than this, actions detailed in the Drought Plan are applied.



#### 5.11.2.1.2.3 Scotland

In 2019, Scotland published its first National Water Scarcity Plan (SEPA, 2019, 2020), which sets out how water resources will be managed prior to and during periods of prolonged dry weather. This is intended to ensure the correct balance is struck between protecting the environment and providing resources for human and economic activity. It sets out (i) high level principles; (ii) the steps that the Scottish Environmental Protection Agency (SEPA) and others are currently taking in preparation for periods of water scarcity; (iii) the assessment methods used to determine the most appropriate response to water scarcity; (iv) the action that will be taken during a period of water scarcity; and (v) the action that others are expected to take.

Scottish Water's Water Efficiency Plan 2015–21 includes measures to educate customers on water efficiency and to reduce leakage in the network. A new mandatory standard was introduced in October 2014 requiring water efficient fittings in dwellings. Per capita consumption of water in Scotland remains high compared to many other European countries, at just over 150 litres per person per day (CCC, 2019c).

Private water supplies are not regulated in the same way as public supplies. Each private supply has an individual owner and local authorities can mandate owners to make changes to supplies that violate health and safety criteria. SCCAP2 highlighted the particular vulnerabilities of private water supplies in Scotland, including a case study from the summer of 2018 when a large number of private water supplies ran dry, requiring local authorities to provide emergency supplies. Currently a grant of £800 is available to owners of private water supplies however, future economic assistance has been recognised as required to better target those in need (DWQR, 2018). The current resilience to drought of sectors outside public water supply is far less well understood. However, these sectors face pressures from climate change, the need to reduce abstraction for environmental protection, and changing patterns of demand in their sector. This means that water supplies that have been reliable in the past may not be reliable in the future.

#### 5.11.2.2 Adaptation shortfall (H10)

There is likely to be an adaptation shortfall for the management of private water supplies in the future. Private Water Supplies are very vulnerable to water scarcity episodes now, as well as from the increased risk due to climate change. There is a need to support rural and remote communities with access to water and to maintain water supply.

Recent research commissioned by the Scottish Government identified major knowledge gaps in relation to the drivers of drought, human influences on the prevention, exacerbation or management of hydrological drought, the collection of data on the impacts of hydrological drought, modelling drought propagation, severity and recovery, and identifying 'normal' in a constantly changing world (Rivington *et al.*, 2020). Multiple recommendations are made to improve the resilience of private water supplies to climate change including:

- building climate change into risk assessments.
- improving monitoring, data collection and flood warnings.

- risk assessment of private water supplies for water quality issues should be extended to include climate-change related issues.
- Policy-prescription is required for technology use.
- wider assessment of the resilience of supply in terms of bedrock aquifer potential.
- the provision of risk awareness and water conservation advice to users.
- identifying the potential for cost effective connection to mains water supply.
- integrating policies and associated research for improving catchment storage potential with those focussed on nature-based solutions for improved ecosystem resilience.
- reviewing and assessing the benefits of centralised management on water supply resilience to climate change in rural areas to inform and enable the use of lower-risk source water services.

There is also an adaptation shortfall due to the lack of consideration of climate change in the risk of chemical contamination of water supplies. No specific policies or strategies have been identified to address this.

There is evidence that it may be more difficult in the future to maintain water quality standards to protect health (Chapter 3: Berry and Brown, 2021) (Box 5.5).

Greater progress in reducing water use by households is also needed to help to manage the risks to households (CCC, 2019g). Statutory water consumptions targets are not yet in place across the UK and could form a crucial part of future adaptation strategies.

#### 5.11.2.3 Adaptation Scores (H10)

<b>Table 5.40.</b> Adaptation scores for risks to water quality and household water supply			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)

#### 5.11.3 Benefits of further action in the next five years (H10)

There are likely to be benefits of further actions to improve water quality by reducing the risk of surface water flooding, such as the development of SuDS (sustainable drainage systems), catchment management, wetland creation (theses are discussed in more detail in Chapter 3 on natural environments), and improvements to bathing water quality. Nature-based solutions also help combat urban heat islands and prevent surface water and river flooding (see Chapter 3: Berry and Brown, 2021).

There is some concern about chemical incidents during flooding and a need for further emergency planning (Chapter 4: Jaroszweski, Wood and Chapman, 2021).

Further activities are also needed to assess the future risks to, and measures that are needed to protect, private water supplies.

#### 5.11.3.1 Indicative costs and benefits of additional adaptation (H10)

There are studies which have considered the overall costs and benefits of national level action to reduce the risk of water scarcity. These include supply side measures, which are discussed in Chapter 4 (Jaroszweski, Wood and Chapman, 2021). They also include marginal abatement cost curves of emergency measures for droughts (Atkins, 2018b), as well as the estimates of costs and benefits of measures to provide household water supply during droughts (National Infrastructure Commission, 2018). Alongside this, there is a complementary set of demand-side measures that can be introduced by homes, many of which are no-regret and low-regret. Water UK (2016) assessed a twin track approach of demand management coupled with appropriate development of new resources and potential transfers as being the most suitable strategy for providing drought resilience in the future. They estimated that total costs per annum for all potential future scenarios (under the Business As Usual base demand management strategy) to maintain resilience at existing levels in England and Wales are between £50 million and £500 million per annum in demand management and new water resource options. If resilience to ‘severe drought’ is adopted, this increases to between £60 million and £600 million and for resilience to extreme drought, between £80 million and £800 million per annum. There are several studies that have looked at demand side measures for households that identify a large number of low and no-regret options. The study by Arup (2008) looked at a range of water saving measures, and estimated costs and pay-back times. A similar study was commissioned by the CCC (Grant et al., 2011) looking at cost-effectiveness of alternative household options, and this was updated by Wood Plc (2019) updating a previous cost-curve study.

These studies identify estimated measures with benefit to cost ratios above 1 for different house types, comparing new build vs. discretionary retrofit. The study provides unit-cost estimates for different measures, and calculated cost-curves to show their relative cost-efficiency. When considering wider benefits from a societal perspective (including avoided GHG emissions), additional no-regret measures are identified. Generally, end-of life upgrades and measures installed in new builds were more cost-effective compared to retrofits. These studies highlight the high economic benefits of further action.

#### 5.11.3.3.2 Overall urgency Scores (H10)

**Table 5.41.** Urgency Scores for risks to water quality and household water supply

Country	England	Northern Ireland	Scotland	Wales
<b>Urgency score</b>	Further investigation	Further investigation	Further investigation	Further investigation
<b>Confidence</b>	Medium	Medium	Medium	Medium

Given the potential for increasing risks to household water supply and quality in the future – particularly for private water supplies – this risk is assessed as needing further investigation across

the UK. Further investigation is required to better understand the degree of vulnerability in different parts of the country, how far some of the beneficial actions identified above could be usefully deployed and the degree to which this could reduce both water quality and supply risks.

## 5.12 Risks to cultural heritage (H11)

Climate impacts on cultural heritage, including tangible and intangible heritage, have already been observed. However, due to the difficulties of measuring and quantifying aspects of cultural heritage, such as the arts, cultural services and intangible heritage, there is a lack of longitudinal research that can be cited as evidence. The potential risks and opportunities from climate change for both intangible and tangible cultural heritage are numerous and include the potential to discover previously unknown heritage. Continued monitoring is essential to inform risk management, especially for areas at risk of flooding from all sources, landslides and erosion. In addition, cultural loss needs to be incorporated into adaptation and resilience thinking. Coastal heritage is particularly at risk from climate change (see H3 and H4) and heritage organizations and communities may need to accept the loss of some heritage assets, particularly for ones on the coast. However, at the coast and elsewhere, it is important that adaptation actions, such as flood defences, are not implemented in a way that damages heritage. Further research and adaptation is required to avoid unnecessary loss of cultural heritage.

### 5.12.1 Current and future level of risk (H11)

This risk describes effects of climate change on cultural heritage, including moveable heritage (museum collections and archives), archaeological resources, buildings and structures, cultural landscapes and associated communities, and intangible heritage (folklore, traditions, language, knowledge and practices) (ICOMOS, 2019). Cultural heritage is intrinsically linked to economic activity across the UK, particularly tourism through heritage tourism, repair and maintenance of historic buildings, regeneration projects, and voluntary and employment work (Historic England, 2017; 2019a; Reilly *et al.*, 2018). The landscape and ‘natural’ places of the UK are closely related to cultural heritage (see Chapter 3: Berry and Brown, 2021) (Historic England, 2020b). Thus, climate impacts that affect heritage assets may have knock on effects upon other sectors, including tourism, health and wellbeing, the natural environment, and vice versa.

#### 5.12.1.1 Current risk – UK (H11)

Cultural heritage, including communities’, groups’ and individuals’ traditional ways of life, has always been exposed to natural processes of exposure, degradation and decay, but climate change is a threat multiplier and exacerbates the effect of current climate risks (Heathcote *et al.*, 2017). Since CCRA2 there has been an increase in research on the mechanisms by which climate hazards currently affect heritage, as well as an increase in assessments of future risks to heritage assets across the UK and evidence of actions being taken.

The main current risks to cultural heritage relate to extreme weather fluctuations including increasing temperatures (heatwaves or fires), precipitation and flooding, coastal processes, and from unintended consequences of climate mitigation and adaptation measures within the heritage sector and across other sectors (Fluck and Wiggins, 2017). An overview of these risks is presented in Table 5.42.

Since CCRA2 there has been an increase in research on the heritage sector's role in tackling climate change (including the arts, culture and museums sectors), and research on the mechanisms by which climate hazards currently affect heritage, as well as an increase in assessments of the future risks to heritage. These initiatives have been supported by a range of bodies such as the Research Councils through grants including the UKRI Climate Resilience Programme and the AHRC Global Challenges Research Fund Urgency Grants on Addressing Impacts on Cultural Heritage resulting from Natural Disasters and Climate Change.

Since CCRA2, research has provided a greater understanding of the threats posed by extreme weather fluctuations to cultural heritage, from historic buildings to communities. As with other aspects of the built environment, all buildings require maintenance, and either poorly applied material or inappropriate material will have a negative impact on both how a building performs and how efficient it can be. Historic England and others have been researching the reasons for the high resistance of some constructions to floods and driving rain, and have identified how greatly this depends on 'traditional' construction systems and materials, specifically solid walls constructed of permeable materials (stone, brick, mortars made of lime and earth), and permeable lime-based renders. By contrast, modern construction types (cavity brick walls, light-weight facades etc.) show little resistance to water, and can prove difficult or impossible to dry after flooding. A combination of laboratory research (e.g. Ridout and McCaig (2017b)), field observations (Ridout and McCaig, 2017a; 2017b) and careful monitoring of flood affected buildings (ibid) in England has demonstrated that, if well maintained with appropriate materials, traditionally constructed buildings can recover well from flooding, often better than their modern counterparts. The impacts of persistent or repeated flooding are less certain, however. Some work has been undertaken to develop toolkits to assess both flood impact and opportunities for the historic environment (e.g. The 'FLOOD' Dataset: User guidance on a GIS dataset mapping historic environmental risk and opportunity in respect to flooding in Worcestershire (Historic England, 2016a)).

Coastal assets are at risk from flooding and coastal erosion; the Dynamic Coastal National Coastal Change Assessment for Scotland has improved understanding of assets at risk significantly (Scottish Government, 2017a). Part of the sea wall protecting Hurst Castle near Milford-on-sea, Lymington, Hampshire collapsed on 26<sup>th</sup> February 2021<sup>19</sup>. Northern Ireland and Wales also have heritage assets located close to coastlines at risk of erosion.

Flooding of museums and archive collections can result in the damage to, or loss of, cultural heritage. In addition, floods can compromise and threaten other cultural practices, reducing community cohesion, damaging traditional or heritage-dependent livelihoods, and resulting in a loss of a shared sense of place from landscapes and places (Hoegh-Guldberg *et al.*, 2014).

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<sup>19</sup> <https://www.bbc.co.uk/news/uk-england-hampshire-56222543>

The impact of increases in precipitation intensity, beyond flooding, have been reported (Historic England, NI communities, Cadw and HES verbal report) but are yet to be systematically captured in published reports and the full extent of harm remains unknown.

Increased temperature and humidity can increase plant and fungal growth that in turn increases the rates of decay for stone and wood structures and the bioturbation of archaeological sites, as well as posing a challenge for indoor heritage, both moveable and immovable (Bertolin *et al.*, 2014; Leissner *et al.*, 2015).

Museum collections and archives hold unique and irreplaceable heritage, which can be damaged by unsuitable indoor environments, particularly poor management of temperature and humidity (Lucchi, 2017). Inadequate management could therefore leave such assets vulnerable to changes in these conditions due to climate change.

Increased temperature and humidity will also impact the huge number of individuals who engage with cultural heritage and cultural recreation through voluntary and employment work and other social activities. Warmer days can increase visitor numbers (see also Risk H2 on the potential for increased engagement with the natural environment) as well as encouraging cultural activities, recreational industries and festivities, and other cultural practices, that facilitate community cohesiveness and placemaking, including increased interaction with cultural landscapes. This has both positive impacts in terms of increasing heritage appreciation and revenue for sites, but also can lead to erosion from increased footfall and trampling (e.g. Pickering (2020)). Increased footfall is now included in some management plans (e.g. Stonehenge and Avebury, Orkney).

Increased heatwave incidence can lead to overheating of heritage buildings, affecting the buildings themselves and any collections within them, as well as being detrimental to staff and visitors (see Risk H1). Overheating in buildings has been identified as a challenge to heritage sites with several sites reporting problems. Contrary to warmer days, it can also result in the decline of footfall and community engagement with cultural heritage due to higher risks of heat exposure and stroke, particularly for the more vulnerable such as older people and children. This may have a particular impact on museums and other cultural activities.

Older buildings have survived because of their durability and adaptability. Continuing to adapt, upgrade, repair and maintain them so they remain useful and viable makes good social, economic and environmental sense (Historic England, 2020a). Research on the importance and effectiveness of maintenance for the resilience of heritage is underway around the UK; closely connected to this is the importance of heritage skills and practices for responding to and adapting to climate risks, and the risk to heritage posed by a loss of those skills (CADW, HES, Historic England NI communities verbal report). A recent Historic England research project, the Value of Maintenance, has shown that a 'stitch in time' approach to maintenance is required (APEC Architects, 2019).

Observed impacts of climate hazards are not systematically reported, and therefore the representation of risks to heritage in published literature cannot be considered representative of the true extent of the risks.

The table below highlights that all manifestations of climate change will affect both tangible and intangible cultural heritage with social and cultural costs and impacts including damage to the wellbeing of individuals and cultural values (IPCC, 2014).

<b>Table 5.42. Observed impacts on cultural heritage from climate hazards</b>		
<b>CLIMATE HAZARD</b>	<b>Impacts on cultural heritage</b>	<b>Examples of observed impacts</b>
<b>Heavy rainfall</b>	<ul style="list-style-type: none"> <li>• Failure of rainwater disposal building envelope, with subsequent moisture/damp problems</li> <li>• Possible increases in roof leakage due to modern roofing designs, including the addition of insulation at rafter level and associated waterproofing materials</li> <li>• Waterlogging of gardens and archaeological site</li> </ul>	<ul style="list-style-type: none"> <li>• Wimpole, Cambs</li> <li>• Westbury court gardens</li> <li>• Studley Royal Water Garden Adren Mill</li> <li>• Derwent Valley Mills</li> </ul>
<b>Drought</b>	<ul style="list-style-type: none"> <li>• Increased risk of subsidence, and shrink swell impact on buildings</li> <li>• Desiccation of waterlogged archaeological sites</li> <li>• Exposure of new archaeological sites</li> <li>• Invisible deterioration of archaeological deposits (buried and full impact only apparent when excavated)</li> </ul>	
	<ul style="list-style-type: none"> <li>• Changes in groundwater levels affecting parks and gardens</li> <li>• Long term impact on resilience of plants and trees</li> </ul>	<ul style="list-style-type: none"> <li>• Nymans Gardens, National Trust site in Sussex</li> </ul>
<b>Flooding (fluvial, pluvial)</b>	<ul style="list-style-type: none"> <li>• Harm to buildings from water ingress</li> <li>• More modern listed buildings may be at risk of catastrophic damage in a flood.</li> </ul>	<ul style="list-style-type: none"> <li>• Carlisle Civic Centre was demolished because it was not possible to dry</li> <li>• Newgale submerged forest</li> <li>• Grinton smelting mill and watercourse</li> <li>• Ironbridge Gorge</li> </ul>
<b>High summer temps</b>	<ul style="list-style-type: none"> <li>• Overheating of buildings leading to problems for fabric, building use, and for sensitive collections.</li> <li>• Increasing demand for air conditioning, which increases problems such as condensation and deterioration of sensitive materials</li> </ul>	<ul style="list-style-type: none"> <li>• Yorkshire Dales Barn</li> <li>• Knebworth House</li> <li>• Ham House</li> </ul>
	<ul style="list-style-type: none"> <li>• Increased visitor numbers: some positive impacts, but increased footfall</li> </ul>	
<b>New pest species:</b>	<ul style="list-style-type: none"> <li>• More common and more rapid deterioration of stone and wood structures</li> <li>• Risk of new pests able to metabolise heartwood building timbers</li> <li>• Increased bioturbation of archaeological sites</li> <li>• Increased water temperatures lead to new pests affecting marine archaeology</li> <li>• Pests and diseases of landscape plants (increased numbers, and new types)</li> </ul>	<ul style="list-style-type: none"> <li>• Appearance of overwintering populations of termites</li> <li>• Asian longhorn beetle</li> <li>• Shipworm</li> <li>• Mompesson House</li> <li>• Castle Drogo</li> <li>• Hardwick Hall</li> <li>• Knole</li> <li>• English Heritage's Operation</li> <li>• Clothes Moth – Brodsworth Hall</li> </ul>

	<ul style="list-style-type: none"> <li>Tree disease threats from e.g. <i>Xyella</i>, Emerald ash borer and Plane wilt will have impact upon our designed landscape</li> </ul>	
<b>Changed growing seasons</b>	<ul style="list-style-type: none"> <li>Impacts on raw materials for repair of buildings</li> <li>Increased plant growth on historic structures</li> </ul>	<ul style="list-style-type: none"> <li>2020 failures of long-straw harvests</li> <li>Blooming of desert plants across Royal Horticultural Society gardens</li> </ul>
<b>Wildfire</b>	<ul style="list-style-type: none"> <li>Potential loss of heritage assets</li> <li>Potential to discover new archaeological sites</li> <li>Changes to landscape management to reduce risk, e.g. fire breaks may harm cultural heritage</li> </ul>	<ul style="list-style-type: none"> <li>Woolsbarrow hillfort, Dorset, was damaged by wildfire</li> <li>Saddleworth Moor</li> <li>Winter Hill</li> <li>Vale of Rheidol</li> </ul>
<b>Coastal change</b>	<ul style="list-style-type: none"> <li>Greatly increased rate of loss of coastal assets</li> <li>Impact of adaptation schemes (e.g. construction of coastal defences)</li> <li>Changes to salinity of groundwater affecting plant growth in historic landscapes, parks and gardens</li> </ul>	<ul style="list-style-type: none"> <li>Visible coastal erosion along ~ 15% of Northern Ireland coastline</li> <li>Immediate vulnerability in Strangford Lough and the Foyle estuary. In Scotland, the Northern and Western Isles most vulnerable (containing two thirds of all high-priority sites)</li> <li>Orford Ness lighthouse demolition</li> <li>Liverpool Bay</li> <li>Orfordness</li> <li>Dunwich Greyfairs</li> <li>Happisburgh Village Hallsands</li> <li>The Garrison, St Mary's</li> <li>Hurst Castle, Hampshire</li> </ul>
<b>Oceanic changes</b>	<ul style="list-style-type: none"> <li>Changes to water chemistry leading to breakdown of marine heritage</li> <li>Fishing is one of the UK's most important maritime activities: changes in distribution of marine species change traditional fishing</li> </ul>	<ul style="list-style-type: none"> <li>Some warm-water marine species (e.g. squid, anchovies) more common and targeted by fishers</li> <li>Disruption of traditional foods, as cod might not be able to persist around the UK in the future if sea water temperatures continue to rise</li> <li>Increased acidification disrupts shellfish growth and harvest</li> </ul>

#### 5.12.1.2 Future risks (H11)

##### 5.12.1.2.1 Future risk - UK

The impacts of climate change over the next century are expected to present serious challenges for the UK's cultural heritage (Fatorić and Seekamp, 2017). The identified range of destructive or problematic impacts is numerous and complex, with arts and culture a dominant feature of people's values, beliefs, practices, and livelihoods, as well as the more recognised and tangible assets of cultural heritage. These very qualities that make cultural heritage both vulnerable and complex can equally facilitate opportunities, such as enabling new discovery of our heritage and encouraging more experience-based approaches, participatory assessments, and storytelling to help towards adaptation and resilience.



#### 5.12.1.2.2 Future risk - England

There is no current overall comprehensive assessment of future risks to heritage in England. Although Historic England reports annually on the Heritage at Risk (HAR) Register (Historic England, 2018) this does not consider future scenarios of climate change. The HAR Register does not currently include all heritage assets (scheduled monuments along with all non-designated assets are excluded). The HAR register does consider some hazards that are linked to current climate risks, such as flooding from all sources, as well as erosion, and plant and insect growth/damage. This reveals that over 23% of listed buildings in England are at risk of flooding, along with ~18% of Scheduled Monuments. More than half of all parks, gardens and battlefields are at flood risk, but this is likely to be less damaging to these assets than to built heritage.

#### 5.12.1.2.3 Future risk - Northern Ireland

Northern Ireland has identified significant implications for buildings from driving rain, and wind and moisture impacts (e.g. Armagh Cathedral) and this is likely to increase with climate change. A strategic risk assessment of potential climate change impacts, specifically coastal erosion and flooding, on archaeological heritage in Northern Ireland was conducted in 2013 (Westley and McNeary, 2014). Visible coastal erosion was present along around 15% of the Northern Ireland coastline and particularly vulnerable areas in the immediate term were Strangford Lough and the Foyle estuary (Westley, 2015; 2019). The dune system at Murlough could also be at risk (Cooper and Jackson, 2018).

#### 5.12.1.2.4 Future risk – Scotland

A recent assessment of risks to coastal heritage assets has been conducted in Scotland. This was informed by a national survey of coastal archaeological heritage threatened by erosion, leading to a revised assessment of 145 sites as high priority with the sites identified as being at highest risk all being in Orkney and the Western Isles. Historic Environment Scotland (HES) has completed the first phase of its Climate Action Plan 2020–2025 (Historic Environment Scotland, 2020).

This represents the first steps in the development of (i) a current climate risk register for the HES Estate; and (ii) a methodology for assessing the impacts of climate change on heritage assets in the wider historic environment. The risk assessment found that 53% of sites are at risk once ongoing mitigating factors and controls, such as routine maintenance, are taken into account. The assessment considered six different natural hazards and found 28 sites that record ‘Very High’ levels of risk in one, or more, of the six hazards investigated: high risk of flooding from rivers, the sea, surface water or groundwater, or high risk of coastal erosion or slope instability.

HES has also published a Climate Change Impacts Guide (OPiT, 2019). The guide identifies many of the risks and hazards of climate change that are facing Scotland's historic environment and offers owners, local communities and carers of historic sites routes to take action, to implement adaptation measures and enhance resilience to climate change.

#### 5.12.1.2.5 Future risk - Wales

A recent assessment of risk was published as part of the new adaptation strategy. The Historic Environment and Climate Change in Wales Sector Adaptation Plan concluded that a large number of assets are potentially at moderate risk from a wide range of climate hazards (Historic Environment Group, 2020). Cumulatively, these risks were identified to be of high significance. Historic landscapes are particularly vulnerable as the cumulative loss of historic assets may affect the integrity and survival of the historic landscape as a whole. For example, the loss of hedgerows and boundaries leads to loss of fieldscape which may alter the spatial arrangement, pattern and understanding of vernacular buildings. The strategy considered the benefits or opportunities from climate change, such as a longer growing season, drying out of buildings and the associated reduced humidity, and changing leisure patterns (Chapter 3, Risk N18: Berry and Brown, 2021). The discovery of new historic assets in desiccated grassland and crops, visible as parch and crop marks, may also be a beneficial outcome. The conversion of formal lawns to meadow in response to the longer growing season in designed landscapes may increase species count in the natural environment and have the benefit of reducing mowing and maintenance costs, but may have a significant impact on the character of historic parks and gardens.

Heritage assets in Wales have been mapped against LiDAR, flood risk data and intertidal data to better understand the risks from climate change. Further work is planned to develop clearer identification and understanding of the threats, alongside an improved evidence base, that will enable prioritisation and plans for adaptation.

#### 5.12.1.3 Lock-in and thresholds (H11)

Lock-in risks due to irreversible change are high, in the sense that most heritage assets are not moveable, but are finite and irreplaceable. This is particularly the case for the many heritage assets located along the UK's coastline.

Thresholds differ between types of heritage asset and climate impacts, and are an area for continuing research and evidence collation. The current literature does not identify thresholds that are observed or operational.

#### 5.12.1.4 Cross cutting risks and inter-dependencies (H11)

Specific interacting risks identified through the previous section include:

- Erosion from rain and wind following wildfire and/or loss of vegetation.
- In combination, impacts of high winds and driving rain impacting building structures.
- Shrink swell resulting from changing levels of groundwater can impact land structures and embankments.
- Increased humidity and increased risk of pests and diseases.

Climate impacts that affect heritage assets may have knock on effects upon other sectors, including tourism, health and wellbeing, and natural environment and vice versa.

- Loss or damage of coastal heritage can affect the local economy where it is dependent on tourism (Roberts *et al.*, 2015; Hall, 2016).
- Maladaptation – responses to climate adaptation that causes harm to heritage assets decreasing their adaptive capacity, increasing repair and running costs.

Cultural heritage has a significant role in placemaking and facilitating cohesive communities and a sense of place, which contribute to wellbeing. Therefore, any damage or loss to cultural heritage could impact wellbeing (Historic England, 2016b, 2019b).

Within cultural heritage, there are interdependencies between tangible and intangible heritage and how loss or damage to one from the impacts of climate change could impact the other. Further research is required to fully understand these impacts.

#### 5.12.1.5 Implications of Net Zero (H11)

The historic environment can support and be supported by the policy imperative to achieve Net Zero carbon emissions by 2050 (Historic England, 2019b; Pender and Lemieux, 2020). Many heritage promotion organisations, such as the National Trust and funding bodies such as the National Lottery Heritage Fund promote high standards of environmental sustainability, including minimising emissions as environmental sustainability, with a particular focus on energy efficiency in buildings.

Measures that improve energy efficiency and therefore increase air-tightness and reduce ventilation may cause overheating in warm weather, poor indoor air quality, and moisture-related damage to the structure and internal environment (Lomas and Porritt 2017). These risks can be mitigated with appropriate ventilation or passive cooling.

Additionally, there is emerging evidence to suggest that understanding the design of traditionally constructed historic buildings or indeed the use of materials in relation to geographic characteristics can counter the view that these buildings are energy inefficient. In fact, disrupting the way these buildings can and should function via maladaptive 'deep retrofit' is a cause for concern, as they were often designed to function in a low-energy, zero-carbon manner (Newman, 2017). The increased emphasis on offshore renewables and attendant infrastructure placed on the seabed has the potential to destroy or damage cultural heritage underwater (McNeary and Westley, 2013).

A benefit of Net Zero will be less outdoor air pollution (less NO<sub>x</sub> and SO<sub>x</sub>) that damages and discolours historic buildings.

#### 5.12.1.6 Inequalities (H11)

The Heritage sector has been severely affected by the COVID-19 pandemic which may have long term financial implications. There may be further implications for deprived areas in accessing funds for adaptation in the future.

Our understanding of future risk, exposure, and the vulnerability of human and mixed human-natural systems to climate change impacts are limited, with a particular lack of understanding

towards socio-cultural dimensions and how these may be understood alongside other biophysical and economic impacts.

#### 5.12.1.7 Observations regarding the impact of COVID-19 (H11)

Since the start of the COVID-19 pandemic there has been an immediate and severe toll on the cultural and heritage sector (Guest, 2020). The dramatic reduction in visitors in spring/summer 2020 led to a substantial drop in revenue which will have lasting impacts. One survey in late March 2020 by the Heritage Fund revealed that at that time 37% of organisations responding estimated they could survive for no more than six months, with 11% expecting to keep going for no more than two months. This lack of revenue, and indeed existence, of some heritage organisations is likely to impact their ability to adapt, and support that adaptation of cultural heritage assets, to future climate change impacts. Further, maintenance and repair work are vital first lines of defence in climate adaptation for heritage assets that have been delayed in many areas. The historic environment sector has launched numerous funds and support mechanisms to help businesses and charities working in heritage.

#### 5.12.1.8 Magnitude scores (H11)

<b>Table 5.43. Magnitude scores risks to cultural heritage</b>					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	Medium  (Low confidence)	Medium  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)
<b>Northern Ireland</b>	Medium  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)
<b>Scotland</b>	Medium  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)
<b>Wales</b>	Medium  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)

Understanding of the current scale of risk has increased considerably across all four countries of the UK, particularly with regards to coastal erosion and flooding. The magnitude of this risk is considered to be medium now and high for the identified climate futures (Table 5.43) due to the large number

of assets at risk and climate change projections regarding increasing temperature, humidity, intense rainfall, drought, flooding and coastal erosion; it is likely that this risk will remain high into the future.

The medium magnitude score has been designated due to the current risk to nationally iconic heritage assets, such as Hurst Castle in England, the immediate vulnerability of the Strangford Lough and the Foyle estuary in Northern Ireland, and the Northern and Western Isles that contain two thirds of all high-priority sites in Scotland. In Wales 12% of Scheduled Monuments and 12% of Listed Buildings are in Flood Zone 3, and numerous nationally important coastal hillforts are at risk of erosion (Historic Environment Group, 2020). With climate change, these current risks are only likely to increase, with others emerging that have not yet been identified.

Confidence levels are lower for England and Northern Ireland than Scotland and Wales as less widespread mapping and risk assessment has been conducted.

## 5.12.2 Extent to which current adaptation will manage the risk (H11)

### 5.12.2.1 Effects of Current adaptation policy and commitments on current and future risks (H11)

#### 5.12.2.1.1 UK-wide

Cultural heritage is impacted by climate change – both directly and indirectly through people's activities as they respond to climate change. Cultural heritage can also provide a source of resilience for communities and inform adaptation by understanding millennia of history from a people-centred approach, and the oral or written history outlining adaptive measures and resilience. Culture, place and resilience are closely related; sustaining local heritage and quality of place is likely to be affected by climate change impacts but can also help build resilience. However, even though culture and heritage sectors are important institutions in most communities, cultural heritage has been largely absent from climate change considerations. Despite the deep connections between climate change and natural and cultural heritage, the experience and expertise of heritage and cultural professionals and local communities is generally not harnessed in identifying how to prepare for and adapt to climate change (ICOMOS, 2019). In many areas, the greatest risk to cultural heritage is from adaptation activity implemented without an understanding of the tangible and intangible cultural context, which can reduce the benefits of adaptation (ICOMOS, 2019).

The cultural heritage sector's response to climate threats is well established and has often taken a 'community-focused' approach to managing the risks, through combining specialised skills in recording and surveying at-risk heritage assets, with the power and enthusiasm of local communities: thousands of sites have been recorded to date. National heritage organisations such as Historic Environment Scotland and the Royal Commission on Ancient and Historic Monuments in Wales have developed and conducted various methods of assessing risk on coastal assets, with further developments planned.

Ultimately, heritage organisations, local communities and other stakeholders may need to accept loss of heritage assets, particularly on the coast, as an inevitability that is part of a natural process. Instead of viewing this as a failure, it can be seen as an opportunity to learn about the past in a way that would not have otherwise been possible (Harkin *et al.*, 2020) and outputs of the Scottish Universities Insights Institute (Scotland 2030 call) funded project on Learning from Loss (Scottish Insight, 2018).

The management of heritage is intrinsically part of the solution to managing environmental change and building adaptive capacity with community knowledge, insights and skills. Whilst legislation is in place across the UK to protect designated sites and buildings, the same does not apply for non-designated assets which comprise most of our heritage. In many cases, historic coastal assets may be designated, with management plans in place, meaning that these parts of the coastline are often better understood and valued, and, in some cases, better protected than adjacent landscapes. Where historic assets are designated, the extent of land protected is often greater than the extent of the heritage asset itself, meaning there is a key role for these assets to play in the management of shorelines. Providing a soft buffer against the energy of waves and wind means that these wider landscapes often play a sacrificial role in protecting other valued assets behind them. The preservation of heritage and the historical character of a landscape has a positive effect on communities, while the ways in which heritage is managed can lead to a better understanding of the effects of climate change in other areas (Fluck and Wiggins, 2017). The archaeological record specifically is an important ‘store’ of past environmental data and provides a crucial long-term perspective on human vulnerability to changing environmental conditions (Jackson *et al.*, 2017) on a scale that other disciplines are often unable to achieve.

Advances made since CCRA2 are primarily around understanding the assets at risk, the impact that could occur, and action to address and prevent these impacts (Historic England, 2020b). Action has increased more around understanding of how climate risks could impact (consequence) rather than how likely they are to occur (probability) and there is a need for further work in this area, as well as a greater focus on action on the ground. However, adaptation needs to be carefully assessed and planned as there is considerable potential for maladaptation through the use, for example, of incompatible materials following flood events (also highlighted in Chapter 4: Jaoroszweski, Wood and Chapman, 2021). Without a change in action/investment and awareness there will be a shortfall in adaptation. In some instances, even with the investment of resources and expertise, the risks associated with climate change will result in loss of heritage assets. The extent of this challenge is currently only beginning to be understood. With resources being a key barrier to adaptation, the severe impacts of COVID-19 on the heritage industry are likely to have an impact for quite some time, and could delay or even put back plans to enhance the climate resilience of the UK’s heritage.

#### 5.12.2.1.2 England

Since CCRA2, awareness of climate risk to heritage has increased. Historic England is undertaking research to map risks to buildings and heritage assets in order to improve decision making (Historic England, 2018). Historic England has also taken measures to increase flood resilience and recovery in historic and traditionally constructed buildings (Appleby Heritage Action Zone – due for completion in 2022).

Historic England research has shown that it is often the response to flooding that can pose the greatest risk to heritage assets, particularly buildings, rather than flood risk itself. Traditional building materials such as lime, wood and stone are extremely resilient, but post flood recovery often promotes the removal of affected materials, harming the historic buildings and reducing their resilience. Assessment of flood impact following floods in Hebden Bridge showed those traditionally constructed buildings that received minimal intervention following flooding recovered more quickly and experience fewer on-going problems in the following months and years. Those where traditional materials were removed and replaced with modern materials took longer to be occupied again and experienced problems with moisture months and even years after the floods (Ridout and McCaig, 2017b).

Historic England submitted its climate change adaptation report to the second, voluntary, round of Adaptation Reporting Power (ARP) (Fluck, 2016), is preparing its next ARP report for submission in summer 2021, and is in the process of developing an adaptation strategy. The Historic Environment Climate Change Adaptation Working Group (HEAWG) was established by Historic England and the Church of England in 2016 to support the historic environment sector in reporting on climate change adaptation (Harkin *et al.*, 2020).

Additional work conducted on understanding and mapping the impact of climate change on heritage include (i) the use of historical documentary sources to develop an evidence base for furthering our understanding of the long-term patterns of coastal change that have resulted from climatic change and sea-level rise ([www.archmanche-geoportal.eu](http://www.archmanche-geoportal.eu)); (ii) a pilot project commissioned by Historic England to develop a methodology for assessing environmental risk to heritage assets along the coast, which has highlighted the challenges of working with environmental data on a national scale (LUC, 2016), and (iii) further work by Historic England to integrate the UKCP18 projections and an update to the BGS-published Coastal Vulnerability Index in future rounds of work (Harkin *et al.*, 2020).

#### 5.12.2.1.3 Northern Ireland

The second Northern Ireland Climate Change Action Plan, 2019–24 (Daera, 2019) included the implementation of the Protocol for the Care of the Government Historic Estate (NIEA, 2012), which introduced requirements for government departments to take heritage more seriously in their own adaptation work including engaging with heritage organisations, as well as implementing the requirements from The Impacts of Climate Change on the Built Heritage Report (NIEA, 2010; Harkin *et al.*, 2020). Further requirements include Government departments conducting climate change risk assessments for heritage assets to inform their adaptation action, and proposing measures to build the resilience of vulnerable sites to these impacts. There is currently no review or evaluation of these action plans.

Current actions being progressed by the Department for Communities (DfC) and DAERA's Historic Environment Division (HED) are as follows:

- DfC has drafted an Action Plan on climate change and the historic environment to include research and the development of appropriate guidance, which is currently being considered internally.
- An action plan document for HED 2021–2022 relating to climate change has been drafted and is going through internal processes of agreement and endorsement.
- Hazard mapping for climate change is underway through a pan UK approach with the DfC's sister organisations (HES, HE, CADW) and led by the National Trust, due for completion by end-March 2021.
- An adaptation manual in conjunction with sister organisations as above is also underway which will relate specifically to managers of historic estates / buildings.
- Energy Efficiency guidance for historic buildings is ongoing.

The Department for Culture's Historic Environment Division commissioned a baseline assessment on the potential impact of climate change on the historic environment (Daera, 2019), but this is not yet available.

Condition surveys considering climate change are being conducted on Northern Ireland Water's Historic Sites (Daera, 2019) that will inform the development of a strategy on climate change and the historic environment.

Individual local authorities have also conducted risk assessments and adaptation plans for the heritage sector. In 2019, Derry City and Strabane District Council conducted a review of the climate risks and vulnerabilities of its heritage assets and museum collections, assessed its current ability to adapt and identified adaptation actions to help improve the resilience of its heritage. This involved an analysis of previous/existing climate impacts, analysis of UKCP18 projections, and assessment of Derry City and Strabane District Council's adaptive capacity. An adaptation plan was produced setting out key actions required and identifying lead and partner organisations, together with a timeframe for action. These actions focus on improving the adaptive capacity of Derry City and Strabane Council, including improving governance, resources, awareness and understanding of impacts and adaptation options to enable action on the ground (Derry City and Strabane District Council, 2020).

#### 5.12.2.1.4 Scotland

Scotland's second Adaptation Programme, 2019 (Scottish Government, 2019a) features climate change impacts and adaptation issues for the historic environment. Historic Environment Scotland (HES) has taken the strategic lead on this in Scotland and recently published its updated Climate Action Plan (Historic Environment Scotland, 2020). With regards to climate adaptation, this focuses on the importance of mainstreaming climate change risk assessment into policy and operations, delivering innovation, developing solutions that support climate change adaptation and mitigation, continuing to promote maintenance and repair as the first line of defence and providing leadership on how to manage the loss of heritage assets. There has been notable progress in the refurbishment of historic buildings taking account of climate change, and a number of case studies and guides have been published by Historic Environment Scotland (HES) since CCRA2.



Adaptation or mitigation responses to climate change may also present challenges in the management of heritage. On the coast, this is made manifest by responses ranging from managed realignment to upgrading or construction of new sea defences. Such defences are unlikely to remain the preferred solution for managing future risk to coastal heritage assets, as they often cause or exacerbate damage in adjacent areas, alongside being costly to install and of high visual impact. Where sites have no hard defence in place, solutions may be sought to try and restore the natural defences lost by erosion. Where this is not possible, loss of heritage sites may have to be accepted, with programmes of excavation and recording conducted to document important information about the site before it is lost (e.g. Links of Noltland, Orkney) (Harkin *et al.*, 2020). In some cases, communities are also moving sites to prevent them from being lost (Graham *et al.*, 2017). These different levels of intervention are currently being explored by organisations such as Historic Environment Scotland and the National Trust for Scotland (Harkin *et al.*, 2020).

#### 5.12.2.1.5 Wales

The Welsh Government's second National Adaptation Plan, *Prosperity for All: A Climate Conscious Wales*, (2019) (Welsh Government, 2019a), highlights the importance of protecting the nation's historic assets from climate change impacts and includes a chapter dedicated to this issue. This was done to recognise the many different sectors that the historic environment blends with, and hence the climate risks they share.

CHERISH (Climate, Heritage and Environments of Reefs, Islands, and Headlands) is a six-year European-funded Ireland-Wales project which aims to raise awareness and understanding of the past, present and near-future impacts of climate change, storminess, and extreme weather events on the rich cultural heritage of the Irish and Welsh regional seas and coast.

The first action for historic environment in the national adaptation plan was to complete and publish the Historic Environment Climate Change Sector Adaptation Plan. Led by the climate change sub-group of Welsh Minsters, the Historic Environment Group (HEG) published its Sector Adaptation Plan in 2020 (Historic Environment Group, 2020). This was intended to raise awareness of the risks and opportunities of climate change for the historic environment and the need to adapt. Key actions focus on in the HEG sector plan are usefully summarised in the national adaptation plan:

- Improving understanding of the threats and opportunities for the historic environment. Through knowledge sharing, spatial mapping, and other research, this key theme sets out to increase knowledge and hence provide better advice for potential adaptation action. An important example of this is the CHERISH project (detailed above).
- Develop methodology and tools to build adaptive capacity. Importantly, this covers the publication of guidance to support adaptation at asset level on such issues as flood resilience for historical buildings.
- Increase resilience by implementing actions to respond and adapt. The Historic Environment Sector Adaptation Plan sets out over 20 headline actions to be undertaken. This includes knowledge exchange and collaboration, mapping and monitoring of heritage assets, sites

and landscapes, identification of prioritised further research, dissemination, promotion and collaboration, training, guidance and action focusing on developing adaptation plans and work programmes for vulnerable areas assets at risk, establishing stakeholder/community groups, and developing new planting regimes.

The Historic Environment Group also collects evidence of adaptation activity relevant to the historic environment to help evaluate progress against the published sector adaptation plan, and identify gaps and priority areas that require further attention.

The Welsh Government has also issued guidance on Flooding and Historic Buildings in Wales (Cadw, 2019). This provides guidance on ways to identify and understand flood risk and prepare for possible flooding by installing protection measures, and explains how to approach the protection of traditional buildings and avoid inappropriate modern repairs in the event of flood damage.

#### 5.12.2.2 Adaptation shortfall

There is clear evidence with regards to progress in terms of developing the evidence base and putting strategic frameworks in place to manage risk, particularly in Scotland and Wales, however there is not yet sufficient action to reduce this risk to a low magnitude. In our view, strategies and plans need to be supported by commitments for action. The key priority challenges and emerging issues which need to be addressed to provide better advice to policy makers, and enable policy to be translated into action, are as follows:

- Communicating the emerging prominence of ‘managing loss’ of heritage assets as a result of climate change, and the need for more robust systems of prioritising assets and intangible heritage for action. But, equally, demonstrating the value of heritage in understanding what the impacts of climate change are, how these assets or landscapes have a valuable role to play in managing the impacts of climate change, and how they can motivate people to take action – the loss of something ‘loved’ or ‘cherished’ is often a catalyst for prompting people into taking action.
- The need for longer-term data capture to better understand the impacts of climate change on heritage assets. This includes understanding the impact of changes in ocean chemistry on decay rates of metal shipwrecks, changing rates of erosion on vulnerable coastlines (and projecting this into the future), impact of ground conditions upon green heritage, buried archaeology and stability of structures, impacts of repeated or prolonged flooding on all types of heritage.
- Whilst increasingly robust data is available on individual environmental threats, e.g. sea-level rise, storminess, wind driven rain, storm surges etc., there is not yet sufficient understanding of how to quantifiably assess the impact of these in combination. This is when the damage will occur, not just from any one single climate driver. Similarly, understanding of impact is much greater than probability.
- A potential conflict between retaining the integrity of historic assets and buildings and enhancing their resilience has been identified, for example the types of materials used to

repair historic assets after a flood event. This highlights the need for greater awareness and cross-sector working to share good practice and ensure that cultural heritage is considered in all areas of policy and plan development, placemaking and action. This will help to build consensus, maximise the co-benefits and reduce the risk of maladaptation.

- Intangible cultural heritage has a lower profile than buildings and assets and is more difficult to protect. More research is required into the impact of climate change on intangible heritage and the adaptation actions required.

### 5.12.2.3 Adaptation Scores (H11)

<b>Table 5.44. Adaptation scores for risks to cultural heritage</b>			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Medium confidence)	Partially (Medium confidence)	Partially (Low confidence)

### 5.12.3 Benefits of further adaptation in next five years (H11)

Further action would be beneficial with regards to mapping climate related hazards that are relevant to heritage, in understanding the vulnerability of different heritage assets to these hazards and identifying those types of assets and locations that are most at risk. The complexity of ownership of heritage assets and the synergies with landscape, land management and the natural environment mean that this is complex. Standardising data collation and facilitating sharing would help further understanding of risks and opportunities.

It is very challenging to estimate the costs and benefits of adaptation for cultural heritage because of its heterogeneity. Costs are very site specific, and benefit analyses involve challenging valuation aspects that include direct and wider economic benefits, but also non-use values, the latter including option, existence, and bequest value. Further, in many cases, adaptation will be part of broader interventions targeting at risk areas, e.g. coastal or river flood management.

For particularly sensitive sites, there are options for monitoring and surveillance in order to recommend both preventative and remedial action. There are also some limited examples in the international literature with case studies (ex ante and ex post), as well as willingness to pay studies that provide some estimates to compare against potential costs (for specific cultural heritage sites). For example, Pollard-Belsheim *et al.* (2014) investigated the effectiveness of adaptation strategies to preserve coastal archaeological sites.

There are also some additional issues with the impact of climate change on artefacts inside museums and galleries. There is some evidence on the options for guaranteeing the appropriate indoor climate, which involve similar issues on the choice between mechanical or passive cooling. Coelho *et al.* (2020) examined such examples and report passive retrofit measures are cost-effective,

but again, adaptation effectiveness will be extremely site specific. Once this is in place, then further action is required across the UK to enhance the resilience of built and natural heritage.

Societies benefit from and are dependent on cultural heritage, which includes ecosystem services (e.g. marine-based livelihoods and food security) and other cultural services (i.e. non-material benefits from ecosystems). However, understanding and attributing the impacts are complicated due to the complexities of assessing, measuring and quantifying cultural services and other social benefits related to cultural heritage. More work needs to be done on the risks and benefits of adaptation options and adaptive capacity, as well as other barriers such as institutional inertia and socio-cultural acceptability of risks.

#### 5.12.3.1 Overall urgency scores (H11)

The overall urgency score is high for all countries with a recommendation for more action due to the high number of assets at risk and gaps identified in adaptation action and planning above. As with the magnitude scoring, confidence levels are higher for Scotland and Wales than England and Northern Ireland due to the additional available evidence.

<b>Table 5.45. Urgency Scores for risks to cultural heritage</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Low	Low	Medium	Medium

#### 5.12.4 Looking ahead (H11)

The majority of cultural heritage experts believe that adaptation to climate change is possible but that further research is needed, along with practical tools (Sesana *et al.*, 2018). Research is required, in particular, to better understand the vulnerability of different types of cultural heritage to climate hazards, and the effectiveness of adaptation options. Targeted research is needed to understand the impact of climate change on intangible heritage, moveable heritage (including museum collections and archives), archaeological resources, and cultural landscapes. The complexity of ownership of heritage assets and the synergies with landscape, land management and land use planning, and the natural environment mean that adaptation planning is complex, involving multiple stakeholders with multiple agendas.

There is also a pressing need for published literature to address the social implications of climate risk to cultural heritage, as this effect will 'vary across societies and over time, depending on cultural resilience and the mechanisms for maintaining and transferring knowledge' (IPCC, 2014).

## 5.13 Risks to health and social care delivery (H12)

Climate change will create disruption to health and social care services due to both the direct effects of floods, heatwaves and other extreme weather on hospitals and other health and care settings, which may damage buildings or disrupt the ICT and transport infrastructure upon which services rely, and indirectly, through the detrimental effects of extreme weather on people's health and wellbeing, which will increase demand for services. These impacts will be felt not only within institutional settings, such as hospitals, residential and nursing homes for older people, or respite centres for disabled people, but will also affect people who receive care services in their own homes, and may prevent people from accessing critical services, such as GPs.

### 5.13.1 Current and future level of risk (H12)

Climate change will create disruption to health and social care services through the effects of floods, heatwaves and other extreme weather on hospitals and other health and care infrastructure. Extreme weather can damage buildings and equipment, and disrupt the ICT, energy, water and transport infrastructure upon which services rely. This assessment is UK-wide – it has not been possible to provide a detailed assessment of current and future risks for each nation.

The evidence about current and future risks relates to:

- Observational studies of the impacts of extreme weather on health service delivery (quantitative and qualitative studies).
- Observational studies and modelling studies of overheating risks in health buildings or specific rooms and building types (hospital inpatient wards, outpatient rooms, delivery rooms).
- Flood risk mapping.

There are many challenges for health and social care providers, especially currently with a global pandemic. Challenges include ensuring continuity of service provision (including the ability of staff to get to work/reach clients), resilience of physical assets for social care and varied care settings (in the context of differing risks from heat/drought/storms/floods), and ensuring their institutional policies and operating practices are responsive to changing needs (for example, adjusting daily routines and management and operating practices in care homes to mediate risk in care settings during heatwaves) (Rajat Gupta *et al.*, 2016).

#### 5.13.1.1 Current and future risk of overheating in hospitals, care homes and related buildings - UK (H12)

Heatwaves cause problems with the functionality of hospitals, as well as the thermal comfort of patients and staff (Carmichael *et al.*, 2013; WHO, 2009a). Reported impacts of heatwaves include:

- Discomfort or distress of patients, and their visitors
- Equipment failure, such as failure of essential refrigeration systems including morgue facilities
- Disruption or failure of IT services
- Disruption of laboratory services

- Discomfort of staff (occupational health issues)
- Degradation or loss of medicines

There is limited published evidence regarding the impacts of recent heatwaves (2018, 2019, 2020) in health and social care settings. Research on the effectiveness of England's heatwave plan (Williams *et al.*, 2019) suggested that health and social care managers found the Heatwave Plan was useful for helping them prepare for emergencies as it prompted them to take actions when alerted to do so. However, the messages did not appear to reach all those working at the frontline with patients, as many nurses said that they were unaware of the Heatwave Plan, and took few or none of its recommended actions during a heatwave alert. Nurses said that they often struggled to protect their patients as their organisations were not well-prepared for heatwaves.

There has been further research on overheating in hospitals, in terms of modelling and observational studies on individual wards/rooms within hospitals. But there is limited assessment of the overall extent of the problem. For example, high indoor temperatures were measured in Royal Berkshire Hospital (ultrasound area of the Maternity and Gynaecology building) during the hot summer of 2018, with temperatures above 28°C on several days (Gough *et al.*, 2019). NHS England Trusts must report instances of overheating as part of their estates return information collection, but there are no systems in place for monitoring in Wales, Scotland, or Northern Ireland. In 2019–20, there were 3,600 instances of overheating above 26°C reported in NHS England Trust buildings (NHS, 2020). However, changes in reporting mean that data on the 'proportion of clinical areas with thermal monitoring' is no longer collected, which makes the instances of overheating difficult to interpret. A report on overheating in healthcare settings in Scotland found anecdotal evidence of overheating issues in four out of the five sites examined within the study (BRE, 2018). The zoning and control of the heating systems, solar gain, and lack of effective natural ventilation were identified as the most significant, and common, contributors to overheating in the five sites that were studied.

Modelling studies indicate that unshaded, well-insulated and thermally lightweight hospital buildings are inherently at risk of overheating, even in a cool UK summer (Fifield *et al.*, 2018). It has been estimated that up to 90% of hospital wards are at risk of overheating during hot weather (Short, 2017). As heat exposure can have disproportionate health implications for the elderly or sick, there has been an increased research focus on overheating in health care facilities, including how different construction techniques may alter heat exposures, and staff awareness of overheating issues. It has been found that modular hospital buildings are at a significant risk of overheating (Fifield *et al.*, 2018). Older hospital wards appear to be more resilient to hot weather conditions, as well as easier to adapt to be climate resilient (Lomas *et al.*, 2012). Conversely, hospitals constructed during the 1960s and 70s using more lightweight methods were found to be at greater overheating risk (Short *et al.*, 2012; 2015). These older wards pose a greater infection prevention and control risk, however, and this has implications for the methods of space cooling that can be used. The building materials and methods of cooling are important, but also some types of wards have restrictions (e.g. secure units) that mean that they are difficult to ventilate.

Health care facilities can have a high density of medical and non-medical equipment, and the anthropogenic and waste heat from this equipment can act to increase indoor temperatures (Gough

*et al.*, 2019). There is anecdotal evidence of equipment, including IT failures, during the heatwaves of 2018 and 2019.

The low awareness of the health risks that heat can cause in vulnerable people is a significant risk in care settings (Gupta *et al.*, 2017). A study in Scotland found that staff were aware of the potential for indirect risks from overheating and staff fatigue was reported as an issue in one site (BRE, 2018). As the design, briefing and management of care schemes largely focuses on the provision of warmth and is reinforced by current regulatory practices, warm environments are prioritised due to its association with 'good care' (Gupta *et al.*, 2016a).

Managing high indoor temperatures within care homes has several challenges (Gupta and Gregg, 2017). These include:

- Lack of awareness or confusion in responsibility on how to manage building systems and controls to avoid overheating.
- Lack of existing physical strategies (such as shading, cross-ventilation) to avoid overheating.
- Diversity in thermal comfort perceptions of residents and staff, and an inability to predict or recognise residents' discomfort regarding heat.
- Engrained habits and practices of carers and residents can result in an inflexibility to adapt routines to short-term changes during hot weather in order to reduce the health risks.
- There is no statutory maximum internal temperature for care schemes. Whilst health and care sector guidance is generally based on excess-mortality related static external maximum threshold temperatures, overheating within the building sector is more specifically related to thermal comfort.

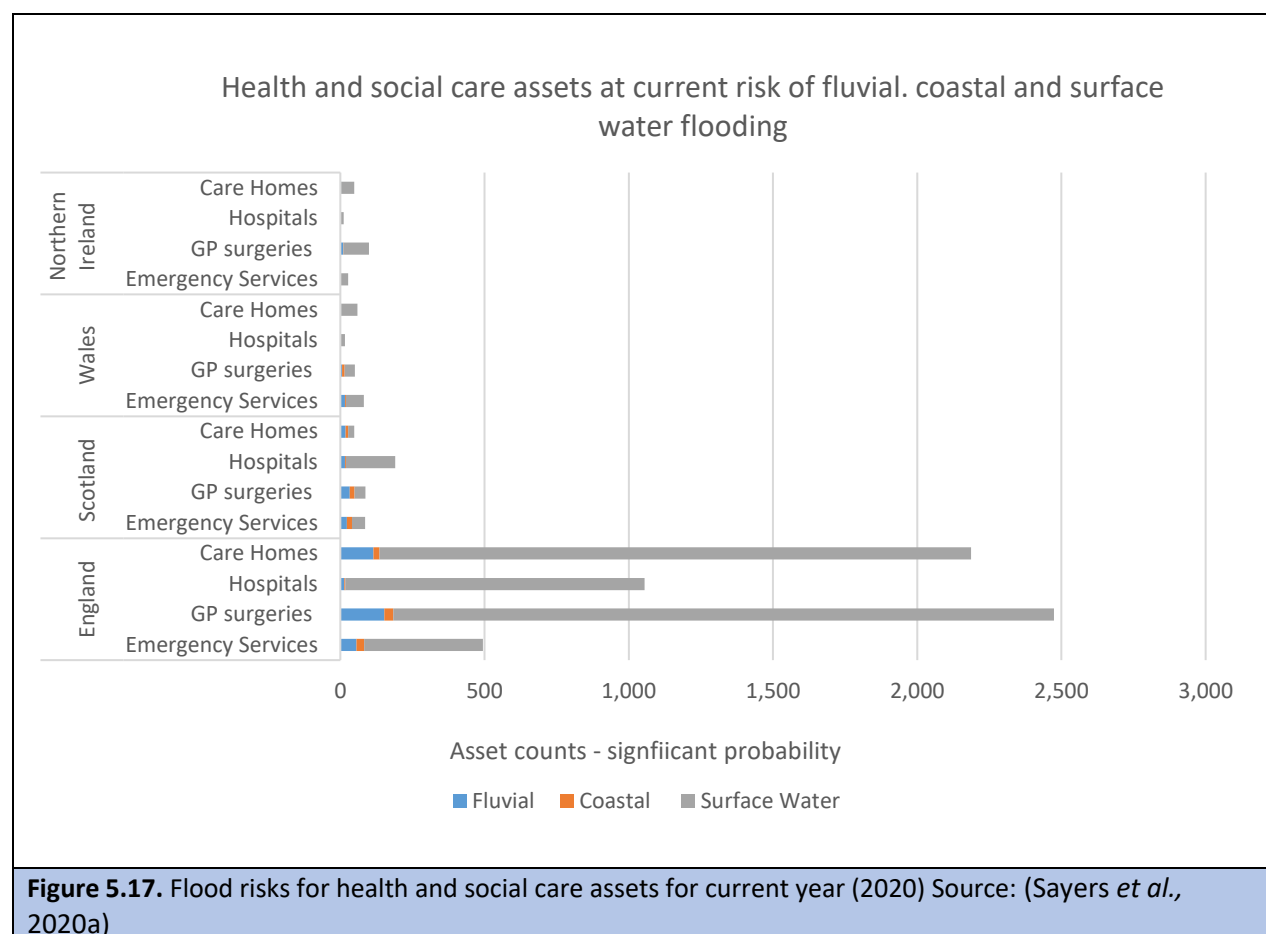
Thermal modelling of future overheating risk in care homes showed overheating in most areas modelled in England (Gupta *et al.*, 2017). Timing and magnitude of overheating was, however, different between the care home case studies. There are many building characteristics and factors which contribute to this, for example, the location of the care homes had a significant impact on the overheating risk.

As temperatures increase, it is very likely there will be an increase in the frequency and intensity of heatwave events and extreme high temperatures, and healthcare buildings will overheat more frequently. Acute services will also need to address the increases in demand during heatwave events. The Met Office estimates that a 'hot' summer such as 2018 has a probability of approximately 10% in the period 1981 to 2000, is currently 10-20%, but this will increase to probabilities on the order of 50% by mid-century (Murphy *et al.*, 2018).

#### 5.13.1.2 Current and future risk of flooding in hospitals and other health infrastructure - UK (H12)

The current and future flood risk of health system assets, including hospitals, care homes, GP surgeries and emergency services has been assessed by Sayers *et al.* (2020a) (see Table 5.46 and Figure 5.17). Approximately 10% of hospitals are situated in areas of significant flood risk in the UK. Surface water flooding is shown to be the greatest risk to health and social care assets. This may be

due to its widespread and spatially distributed footprint when compared to fluvial flood events of comparable magnitude.



Flood events have damaged health care infrastructure and equipment in recent years but there is no overall assessment of the total impact of flooding in either disruption to services or financial costs. There have been several reported examples of impacts on health services from flooding events, particularly in terms of both patients and staff unable to access services:

- A qualitative study after flooding in Lincolnshire showed that floods reduced capacity in the health system to cope with routine health provision (Landeg *et al.*, 2019).
- Hospitals have also been affected by flooding in England. A comprehensive study of rainfall and ambulance services in England has shown that even low-magnitude floods can cause a reduction in ambulance response times, leading to impacts in provision for vulnerable groups at locations such as care homes, sheltered accommodation, nurseries and schools (D. Yu *et al.*, 2020).
- In January 2021, Storm Christoph nearly led to the flooding of a COVID-19 vaccine factory in Wrexham. Workers pumped water from the area and cleared gullies around the site after the building experienced mild flooding.

In all nations, a significant proportion of health and social care assets are at risk of flooding and this will increase by 2050 and the 2080s in scenarios of both 2°C and 4°C global warming in 2100 (assuming no change in infrastructure). Table 5.46 shows the increase in risk of 1 in 75-year floods



for hospitals, GP surgeries, emergency services and care homes (Sayers *et al.*, 2020a). The largest increase in risk is in England.

Table 5.46. Current and future flood risk for health and social care assets with different combinations of climate change pathways and population scenario, with Reduced Whole System (RWS) adaptation: numbers assets in probability band “significant”. Source: Sayers <i>et al.</i> (2020a), see reference for further details.									
	Present	2050s				2080s			
Population Projection		Low		High		Low		High	
Climate pathway (global warming reached in 2100)		2°C	4°C	2°C	4°C	2°C	4°C	2°C	4°C
ENGLAND									
Emergency services	495	729	835	735	842	841	985	854	1001
GPs surgeries	2474	3662	4205	3690	4235	4243	5056	4299	5127
Hospitals	1055	1336	1451	1350	1466	1463	1617	1491	1649
Care homes	2187	3286	3864	3315	3879	3901	4745	3962	4823
SCOTLAND									
Emergency services	86	103	106	104	107	104	115	106	117
GPs surgeries	87	115	127	116	128	123	135	125	137
Hospitals	190	252	262	254	264	260	267	264	272
Care homes	49	59	61	59	61	59	63	60	64
WALES									
Emergency services	81	98	106	100	108	103	121	108	127
GPs surgeries	51	55	59	56	60	57	70	60	73
Hospitals	16	17	17	17	18	17	18	18	20
Care homes	48	71	78	73	80	77	87	81	94
NORTHERN IRELAND									
Emergency Services	27	33	37	35	38	35	40	38	43
GPs surgeries	99	128	130	131	133	126	133	133	144
Hospitals	11	16	16	16	17	16	17	17	19
Care homes	48	60	63	62	65	61	67	65	73

#### 5.13.1.3 Lock-in and thresholds (H12)

To avoid lock-in, there is a need to ensure new and refurbished hospitals and care settings are designed for the future climate (Fifield *et al.*, 2018). A failure to plan heat management in new care homes and care in the home could lock-in large numbers of people to heat risks (Watkiss *et al.*, 2019b).

Future care policy could have important lock-in risks, e.g. a policy towards greater independent care in the home might actually increase future risks. This is a risk where there is a potentially high need to consider future pathways (and adaptive management) because the UK is likely to experience a

growing risk (extreme heat) that it has not faced historically, and that will involve potentially large levels of change depending on the future rate of global warming.

There are thresholds related to overheating risks for buildings and rooms or wards. For example, thresholds are used for tolerable indoor temperatures in modelling in care homes (26°C). The Northern Ireland Nursing Home Standard requires temperatures in areas occupied by residents to be between 19°C and 22°C. It is not possible to develop population wide thresholds specifically for health and social care systems.

The heat alert thresholds within the Heatwave Plan for England include actions for the health and social care agencies and professionals. These are currently being updated, based on new evidence regarding population level impacts. Heat alert thresholds are operational thresholds for managing episodes of hot weather. It is important to note that many heat related occur on days that are not 'alert' days, and therefore strategies take into account a range of measures.

As the climate warms, there are likely to be thresholds for comfort, especially for patients and health/social care professionals, that are exceeded. There will also be toleration thresholds for equipment that are likely to be exceeded unless action is taken.

#### 5.12.1.4 Cross-cutting risks and inter-dependencies (H12)

As the risks relate to risks from heatwaves and flood events, some of the evidence described in Risk H1 (higher temperatures) and Risks H3/H4 Flooding and coastal change are relevant here.

Disruptions to infrastructure from extreme weather can have knock-on impacts to delivery of health and social care (WSP, 2020).

- Power or IT outages can cause significant issues. In 2015, a flood caused a power cut to the Royal Berkshire hospital. The hospital had to close its accident and emergency department to all but life-threatening conditions.
- Disruption to transport infrastructure (for example roads being flooded) can cause transport delays and impact ambulance and emergency vehicles (Yu *et al.*, 2020).

#### 5.12.1.5 Implications of Net Zero (H12)

The health systems in England, Wales and Scotland have commitments to decarbonise and reduce emissions. NHS England has published a report that more clearly defines the pathways and interventions required to achieve the Net Zero ambition (NHS England, 2020). As has been addressed in detail elsewhere (Risks H1, H2, H5), measures undertaken to increase energy efficiency in buildings need to take account of risks to overheating (and indoor air quality).

Dynamic thermal simulation of a retirement village retrofit to nearly zero energy standards was found to increase the overheating risk of the buildings, with mitigating options unable to eliminate overheating risk (Salem *et al.*, 2019).

## 5.12.1.6 Inequalities (H12)

Inequality in access to health and social care exists within the UK. There has been little additional evidence regarding inequalities in access to care in relation to extreme weather events.

## 5.12.1.7 Magnitude scores (H12)

Due to the large number of assets at risk of overheating and at risk from flooding, the magnitude of risk is medium to high in all countries (Table 5.47). Both economic costs of impacts (damage to infrastructure) and disruption to services are considered here. However, there is a lack of evidence on these risks leading to a medium level of confidence. Overheating risks are likely to be significant in England and Wales after mid-century, especially under high rates of warming. The costs of damage to hospitals from flooding can be significant but there is no overall estimate of these costs on a national basis.

<b>Table 5.47. Magnitude scores for risks to health and social care delivery</b>					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (High confidence)	High (High confidence)
<b>Northern Ireland</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)
<b>Scotland</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)
<b>Wales</b>	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)	High (Medium confidence)

### 5.13.2 Extent to which current adaptation will manage the risk (H12)

#### 5.13.2.1 Effects of current adaptation policy and commitments on current and future risks (H12)

##### 5.13.2.1.1.UK-wide

The health and social care systems in the UK are devolved, and also complex in terms of the multiple agencies that deliver care. There are national regulators who are responsible for standards of care in hospitals, care homes and other related services. Local authorities are responsible for commissioning some community care services. Many care homes are also owned or managed by the private sector or third sector.

There is still relatively little published evidence on the evaluation of emergency planning in hospital and other health care settings. There have been several papers and reviews that address resilience to climate risks more generally in health systems (Marinucci *et al.*, 2014; Paterson *et al.*, 2014). The World Health Organisation has developed a framework on health system resilience to climate change (WHO, 2018b). The US (CDC) has also developed the Building Resilience Against Climate Effects (BRACE) framework to support health officials to develop strategies and programs to prepare for the health effects of climate change.

A range of building interventions or building designs are available to address overheating risks (see also discussion in Risk H1). Even with good evidence of effectiveness, there are, however, limitations in addressing overheating in care settings. Building types for hospitals and care homes vary widely and adaptation measures may not be universally effective. Even within the building level, wards can respond differently than other type of healthcare rooms (e.g. outpatient rooms). Measures that mitigate overheating risk or enhance resilience will need to be tailored to each building's construction and location, and each individual space's orientation and occupancy pattern.

##### 5.13.2.1.2 England

There has been some action to address overheating in hospitals and health care buildings in England. DHSC and its arm's length bodies have developed measures to improve patient safety and increase resilience to heatwaves in health and social care buildings.

For example, DHSC have been working with the NHS to address overheating risk in mandatory Green Plans (formerly known as Sustainable Development Management Plans – SDMPs). The NHS aims to embed adaptation into daily practice by 2023, by including it as a key element of Green Plans. Green Plans must be submitted by all NHS providers. This will be supported by guidance from Greener NHS, NHS England and NHS Improvement (NHSE&I). The NHS Standard Contract is mandated by NHS England for use by commissioners for all contracts for healthcare services other than primary care. The Service Conditions of the full-length NHS Standard Contract 2020/21 includes conditions that require trusts to adapt the Provider's Premises and the way services are delivered to mitigate risks associated with climate change and severe weather.

From April 2017, the NHS has required Trusts and commissioners to submit information on:

- the percentage of clinical areas covered by thermal monitoring
- the number of overheating events in clinical areas
- the presence of an organisational adaptation plan

This requirement has now been removed, so there is now less information on overheating risks than in previous years.

NHS England has undertaken a review of emergency planning preparedness and response in 2019 but the results are not yet available. All NHS Trusts in England have to respond to the survey of emergency planning, following a commitment from NHS England to address the response to extreme weather.

The Heatwave Plan for England includes specific guidance for care homes (and persons needing care at home) (PHE, 2018b). Care home owners and managers consider building designs to reduce overheating under current and future climates as a low priority, and due to perceived conflicts between cooling and occupant requirements, there is a lack of investment in adaptation strategies (Gupta *et al.*, 2016b). There is risk of lock-in from inappropriate building designs for care homes.

The Greater London Authority piloted an audit process to produce evidence-based recommendations for reducing the occurrence of summertime indoor overheating and exposure to elevated temperatures in care settings by residents (Oikonomou *et al.*, 2020). The report found that care homes could benefit from simple measures incurring minimal or no cost at all, such as switching off unnecessary heat sources and applying rules for window opening and use of curtains, to highly efficient, albeit more complex and expensive, solutions that could be implemented in the longer term. These include the application of external shading, high albedo finishing materials and green roofs. Occupant behaviour plays a significant role in overheating reduction.

The Care Quality Commission (CQC) has a role to oversee the quality of care in England. CQC have engaged in additional work to raise awareness about overheating risk, for example through publicity of #TempAware on social media<sup>20</sup>. Assessments of health and care services focus on the importance of people experiencing a safe environment that is responsive to their personal needs. This includes considering the building temperature and how individual hydration and nutritional requirements are being met, and is underpinned by the guidance developed by the CQC.

The Care Quality Commission (CQC) undertake inspection of residential care homes but do not explicitly assess the risk of overheating or heatwave management. However, they inspect for evidence of:

- How risks to people are assessed and their safety monitored and managed, so they are supported to stay safe and their freedom is respected.
- How equipment, which is owned or used by the provider, is used to support people to stay safe.

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<sup>20</sup> <https://www.cqc.org.uk/news/stories/stay-tempaware-during-heatwave>

- How the premises and safety of communal and personal spaces (such as bedrooms) and the living environment are checked and managed to support people to stay safe.
- How the provider manages risks where they provide support in premises that they are not responsible for.

#### 5.13.2.1.3 Northern Ireland

The Department of Health (DoH) in Northern Ireland has three main responsibilities:

- Health and Social Care, including policy and legislation for hospitals, family practitioner services and community health and personal social services.
- Public Health, which covers policy, legislation and administrative action to promote and protect the health and well-being of the population.
- Public Safety, which covers policy and legislation for fire and rescue services.

The second Northern Ireland Climate Change Adaptation Programme (Daera, 2019) highlights the risks to health and social care delivery from climate change, including from hazards such as extreme heat and flooding, but there are no specific actions listed in the programme to address these hazards in health and social care settings.

Care homes have guidance for temperature ranges (Revised Residential Care Home and Revised Nursing Homes Standard – *‘the temperature in areas occupied or used by residents should be between 19°C – 22°C’*). A stakeholder event held in 2015 found that there was limited action on health and social care in adaptation planning. Climate change adaptation was not seen as a priority. The ability to adapt older, existing health and social care buildings in terms of overheating can be difficult due to the building design. There is also a perceived conflict with using air conditioning as a retrofit (stakeholder event 2015 run by Climate NI).

#### 5.13.2.1.4 Scotland

The second Scottish Climate Change Adaptation Programme (Scottish Government, 2019a) makes reference to a large number of different policies and projects designed to help the health and social care sector adapt to climate change.

- Climate Hazards and Vulnerabilities Risk Screening Tool for Healthcare Assets: launched in summer 2019, the tool aims to inform NHS Scotland risk assessment and planning processes, including identification of the risk of damage and loss to healthcare assets and sites.
- NHS Board Climate Change Risk Assessments and Adaptation Plans: NHS National Services Scotland (NHS NSS) recently undertook an NHS Scotland-wide climate change impact assessment to consider the key climate risks for each NHS Board. This included a flood risk assessment of over 250 NHS sites. Building on these initial studies, NHS NSS have now developed a Climate Change Risk Assessment tool which enables NHS Boards to assess their climate risks and integrate these assessments into resilience planning at each site. Work is now in progress across all NHS Boards to transition from the initial impact assessment to full adaptation plans.

- NHS Scotland's Sustainability Strategy will provide clear ambitions and actions against 16 areas of focus, including Climate Change Adaptation. NHS Scotland's Sustainability Assessment Tool (NSAT) enables NHS Scotland Boards to assess their sustainability performance across different areas of focus, including Climate Change Adaptation.
- NHS Standards for Organisational Resilience. These are designed to support NHS Boards to enhance their resilience. There are 41 standards that cover a range of topics that NHS Boards need to be prepared for, including climate change.

As mentioned above, territorial NHS Health Boards are required to undertake climate change risk assessments on their estates and have developed tools to undertake such assessments and integrate these assessments into resilience planning at each site. The NHS Highlands region has completed the first risk assessment, but the results are not (yet) publicly available. NHS Health Scotland is producing a report on the links between health inequalities and climate change, with a physician statement setting out key issues. A report on overheating in healthcare settings in Scotland is also in progress.

#### 5.13.2.1.5 Wales

The Welsh Government and NHS Wales have made progress in increasing resilience to extreme weather. A Building Note (Welsh Government, 2017) focuses on the strategic approach to resilience planning for healthcare estates, procurement, design and planning, building services, and engineering. This focuses on impacts of severe weather incidents, flood risk, coastal change, water supply and changes to biodiversity and landscape and wildfires. This is a comprehensive tool for managing the estate and assets. However, the extent of implementation and influence is not understood, although reference to it does not feature in elements of health and social care planning in Wales.

Some hospitals have installed sustainable urban drainage systems (SuDS) to address risks from (pluvial) flooding. Examples include the Princess of Wales Hospital in Bridgend and Cynon Valley Community Hospital in Rhondda in Wales.

River Basin Management Plans for Western Wales, the Severn and Dee Rivers and 11 catchment summaries focus on climate risks soils, water, trees, biodiversity, water demand, and supply and character. They provide only a broad indication of risks because health and social care assets are not identified, but included within the broad category of non-residential properties.

The Welsh Government's national adaptation plan, Prosperity for All: A Climate Conscious Wales (Welsh Government, 2019f), includes a policy commitment to address the climate risks through the 'SH3 Update' and revise plans and advice in line with research to increase understanding of the future risk extreme weather brings to health and social care delivery via increasing understanding and improved contingency planning. However, there is little evidence of discourse and analysis on climate risk to health and social services in strategy or governance. A climate change Health Impact

Assessment commissioned by Public Health Wales is underway, and includes impacts on healthcare delivery.

#### 5.13.2.2 Adaptation shortfall (H12)

For all four UK countries, policies or plans are in place to increase adaptation within the health system. Our assessment is that this will only partially address the risks now and in the future, but not fully allow risks to be reduced to low magnitude levels. Adaptation actions are likely to be insufficient for higher levels of warming.

There is less evidence regarding policies in the social care system, including care homes. Current evidence shows that there may also be issues about the implementation of plans throughout the health systems, particularly for frontline staff.

As well as a lack of available evidence on action being taken for Northern Ireland in particular, there are some specific gaps in planning and implementation remain, including:

- Lack of awareness of heat risks and responses among frontline staff, as shown in care homes (Gupta and Gregg, 2017) and hospitals (Williams *et al.*, 2019). Gupta and Gregg (2017) found that in care settings specifically there was:
  - A lack of existing physical strategies (such as shading, cross-ventilation) to avoid overheating.
  - Diversity in thermal comfort perceptions of residents and staff, and an inability to predict or recognise residents' discomfort regarding heat.
  - The possibility of inflexibility in adapting routines to short-term changes during hot weather in order to reduce the health risks due to engrained habits and practices of carers and residents.
  - No statutory maximum internal temperature for care schemes; whilst health and care sector guidance is generally based on excess mortality-related static external maximum threshold temperatures, overheating within the building sector is more specifically related to thermal comfort.
- Lack of monitoring of indoor temperatures in health and social care settings. The requirement for NHS Trusts and commissioners to report on overheating risk and incidents of overheating through the Estates Returns Information Collection (ERIC) in England has been removed.

Further, evaluation of the heatwave plan for England (Williams *et al.*, 2019) concluded that:

- Heatwave planning was largely seen as an exercise in emergency preparedness and focused on 'warning and informing' through the alert system, rather than as a strategic objective of long-term public health and environmental planning.
- The role of Clinical Commissioning Groups (CCGs) in planning and implementing local heatwave plans was not clear; in some areas CCGs were reported to be taking a key role in



planning and co-ordinating the health response, while in others they were said to be acting in a more supportive role, with NHS England taking the lead.

- Emergency planners, mainly in local authorities and acute trusts, said that they adopted a ‘wait and see’ approach, employing professional judgment before escalating actions during a heatwave.

The evaluation of the Heatwave Plan indicates gaps in implementation, particularly among front line staff. There is limited evidence regarding actions in Wales and Scotland specifically, so we assume that some of the issues highlighted above may apply across the UK, but our confidence in this assessment is lower.

### 5.13.2.3 Adaptation Scores (H12)

<b>Table 5.48. Adaptation scores for risks to health and social care delivery</b>			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (High confidence)	Partially (High confidence)	Partially (Medium confidence)	Partially (Medium confidence)

### 5.13.3 Benefits of further adaptation action in the next five years (H12)

This risk needs to be managed strategically at a national level. Regional/local level climate risk assessments should be carried out by Trusts, Health Boards and local government social services (where these are not already happening) to help them plan forward with climate risks in mind. As highlighted in the sections above, a particular issue is around heat risks in care settings, and thus there are similar issues for passive versus mechanical cooling options as for all buildings (see H1). There are obvious potential benefits from ensuring new care homes and hospitals are designed for the future climate. This is particularly important given the high risks and potential for lock-in involved, i.e. the higher costs of retrofitting later. There are also potential options for retrofitting existing care homes and hospitals.

For hospitals, there is some literature on hospital design (including retrofitting) that emphasises passive approaches (Giridharan *et al.*, 2013; Fifield *et al.*, 2018) which highlight the potential benefits of such designs, but also highlights that other drivers, notably economics, are preventing uptake. However, the costs and benefits of actions, especially for retrofitting existing buildings, will be very site specific.

There is some analysis of potential adaptation options for care homes (Oikonomou *et al.*, 2020) (Gupta *et al.*, 2016a; PHE, 2018b). These studies identify a range of options, including in care home operation (monitoring, early warning, emergency response), passive and mechanical cooling, and enhanced regulations, standards and guidance from care sector bodies and Government departments. Some initial work has been undertaken to explore a cost-benefit evaluation of building

adaptations designed to protect against heat risks to residents of care homes in England (Ibbetson, 2021). The work found that various physical adaptations have the potential to at least be cost-effective and reduce heat risk. For example, in one case study, external window shading was estimated to reduce mean indoor temperatures by 0.9°C in a ‘warm’ summer and 0.6°C in an ‘average’ summer. In this case, for a care home of 50 residents, over a 20-year time horizon and assuming an annual discount rate of 3.5%, the monetized benefit of reduced Years of Life Lost (YLL) would be between £44,000 and £230,000 depending on which life-expectancy assumption is used. Although this range represents appreciable uncertainty, it appears that modest cost adaptations to heat risk may be justified in conventional cost-benefit terms even under conservative assumptions about life expectancy and should therefore be considered as an important complement to operation responses.

Other adaptation options can be considered low regret (i.e. heat management plans, some passive ventilation measures). Further investigation of the range of adaptation options across the UK would be highly beneficial.

Given these gaps in understanding, further action is therefore needed to specifically address the risk of overheating in residential care buildings. Adaptations through design measures (such as glazing improvement (where needed), draught proofing, shutters, reflective surfaces, green cover and green space, and ceiling fans) can help to reduce the risk of overheating in the next five years (see also discussion of housing interventions above).

Monitoring of indoor temperatures and other indicators would be an additional response. Indoor temperature/ thermal comfort monitoring could be installed in a stepwise method, to monitor changes over time.

The COVID-19 pandemic may have long term implications for the resilience of the health and social care sector. The pandemic has caused additional stress on the health and social care system due to increased demand (likely to last until 2022) and additional pressures on local finances (likely to last longer term).

#### 5.13.3.1 Overall urgency scores (H12)

<b>Table 5.49. Urgency scores for risks to health and social care delivery</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Medium	Medium	Medium

Our assessment is that the progress in research and action at the national and local level to implement strategies to address climate risks goes some way to managing the increasing risks from climate change, but this is only partial. Given the medium to high projected risks in the future due to climate change combined with this adaptation shortfall, the risk has evaluated as more action

needed in all countries. Confidence is medium, as there are gaps in the evidence available about how far implementation of adaptation strategies is underway, particularly at the local level across the UK.

#### 5.13.4 Looking ahead (H12)

Implementation of indicators and monitoring methods to track adaptation actions and resilience across the health and social care sector is needed in advance of CCRA4. There are key reporting issues that could be improved in order to get a better understanding of the preparedness of this sector to climate change. Research on technologies, including building design is needed that is appropriate for care settings.

### 5.14 Risks to education and prison services (H13)

Climate change is likely to cause disruption to education and prison services. The majority of current evidence on climate risks and education relates to the impact of heat in schools. Children are more vulnerable to heat risks, especially young children and those with special needs, and are reliant on teachers and other adults for support. There is evidence of planning in line with 2°C and 4°C climate scenarios being developed in England and Wales for both schools and prisons. However, further adaptation measures are essential in each nation to avoid lock-in with building designs and adapt to the future risks of overheating, flooding and other climate hazards.

#### 5.14.1 Current and future level of risk of education (H13)

The evidence base for current and future risks is fairly limited for devolved nations. It is not possible to assess current and future impacts by UK country, but risks for education and prison services are presented separately.

##### 5.14.1.1 Current risk (H13)

###### 5.14.1.1.1 Current risk: Education sector (H13)

The majority of current evidence on climate risks and education services relates to the impact of heat in schools. Children are more vulnerable to heat risks, especially young children and those with special needs, and are reliant on teachers and other adults for support, knowledge and guidance, particularly at early school age (GLA, 2020). The Department of Education has highlighted that Special Education Needs schools are a priority for heat risks. High indoor temperatures have adverse effects on health and wellbeing (see Risk H1) but also effect cognitive performance and the ability to learn (Wargocki and Wyon, 2006).

There is no current evidence regarding the prevalence of high indoor temperatures in schools and educational buildings across the country. However, local studies and evidence from pupils and staff have identified current serious issues:

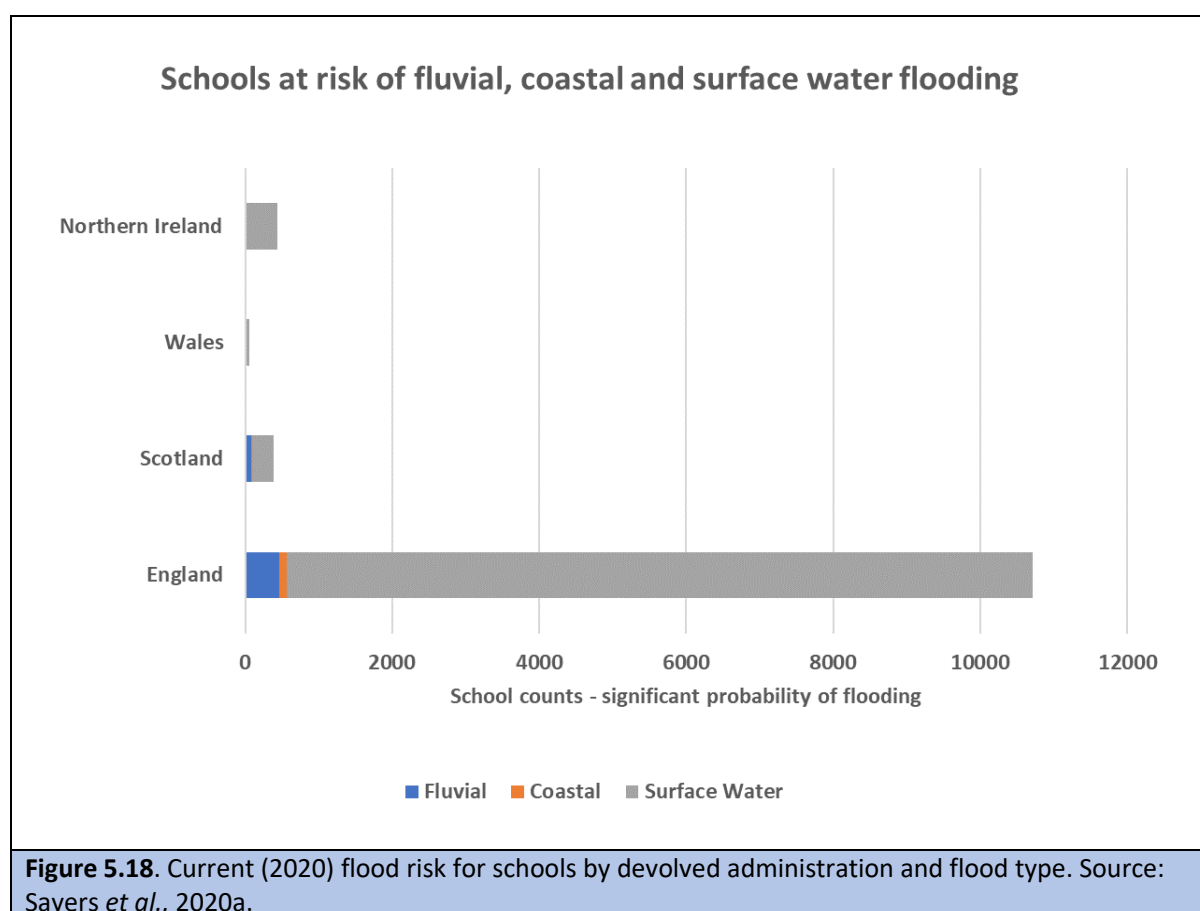
- A study in Southampton revealed that of nine factors, the summer heat had the largest detrimental impact on learning experience (Arup, 2014).
- Schools in London have also reported that concentration levels of children had been affected as a result of high temperatures in recent years (GLA, 2020).
- A survey of teachers found that 90% reported taking additional measures to reduce the classroom temperature, including purchasing portable air conditioners (Environmental Audit Committee, 2018b). The majority of respondents reported that high temperatures had an impact on student performance, with half reporting that the reduction in productivity was 'significant'.
- Some new student residences experienced internal temperatures above 30°C, partly because window openings were inadequate (CIBSE, 2020).

Building design of schools is key determinant of heat risks. Some naturally ventilated modern schools often have more problems with increased risk of overheating. System-built schools (e.g from the 1960s and 1970s), Victorian schools and some well-designed new schools are at a lower risk of overheating due to having significant thermal mass and cross ventilation (Teli *et al.*, 2011; Teli *et al.*, 2012; CIBSE, 2015). Overheating problems in older schools may be due to retrofitting and poor ventilation (Montazami *et al.*, 2015), particularly when retrofits were to address space heating in winter (DCLG, 2012; Teli *et al.*, 2017). Newly built schools may also present a risk if poorly designed, without taking heat risk into consideration (GLA, 2020). GLA (2020) provided an example of a new primary school building equipped with modern control systems, high levels of insulation and glass, which experiences regular overheating. The complexity of the control system was found to make temperatures more difficult to manage rather than easier. Overheating risks can occur outside of the school building in playgrounds and surrounding areas due to a lack of shading or through trapping of heat in surfaces such as tarmac and dark coloured materials (GLA, 2020).

Indoor temperatures can be difficult to regulate due to high classroom occupancy, activity and the volume of IT equipment (Lykartsis *et al.*, 2017). Schools built with mixed mode or mechanical ventilation systems may be more able to comply with current overheating criteria but are not necessarily more resilient to future climate change due to the fixed ventilation rates of mechanical systems (Lykartsis *et al.*, 2017).

10,150 schools in England are assessed as being exposed to a significant probability of flood, along with 432 and 292 schools in Northern Ireland and Scotland respectively (Figure 5.18) (Sayers *et al.*, 2020a). The majority of this risk is associated with surface flooding. There is also concern that many school buildings have flat roofs and are more susceptible to damage from heavy rain. However, there has not been an overall assessment of flood risk to schools. Severe damage to buildings entail significant costs, and alternative venues need to be found to ensure continuity of education. For example, a primary school in Northwich that was severely damaged by Storm Christoph could not be used for two months and pupils were receiving lessons in the local leisure centre. In 2007, 158 London schools flooded due to heavy rainfall and surface water flooding (JCSC, 2019). The 2007 floods resulted in school closures across England with a total of 400,000 pupil school days lost. which was estimated to have an economic cost of £12 million, not including damage to property (EA, 2010).

As mentioned in risk H5, an additional risk that has been identified is landslides, particularly in relation to coal tips in Wales. The Aberfan disaster in 1966 involved a rainfall-induced landslide of a coal tip onto a school and houses, killing 116 children and 28 adults. In February 2020, a major slope failure followed heavy rain at the Llanwonno tip near Tylorstown, prompting an urgent review of legislation and plans for monitoring and remediation (Welsh Government, 2021e). Most of the 2,000+ coal tips in Wales are in the south of the country, and 294 have been identified as high risk (Fairclough, 2021). Annual mean precipitation in South Wales has increased over the last century (Chapter 1: Slingo, 2021), and we suggest that it is possible that climate change may have already increased the risk of future slope failures.



#### 5.14.1.1.2 Current risk: Prison services

There is limited published evidence of the impact of climate hazards on prison buildings and inmate and staff health in the UK.

UK prisons are vulnerable to high ambient temperatures due to the current strategy from central government promoting insulation and specific building materials (Jewkes and Moran, 2015). In the summer months, temperatures exceed comfortable conditions due to thermal efficiency and limited natural ventilation. The HM Inspectorate of Prisons report included concerns from inmates during inspections which included difficulty of breathing, continuous heating, high ambient temperatures in cells and limited oxygen from poor ventilation (HM Inspectorate of Prisons, 2017). The Ministry of

Justice (MoJ) received nearly 500 reports and complaints of overheating in 2016–17 (Environmental Audit Committee, 2018c). Solutions such as air-cooling technologies have been suggested to not be acceptable for prison conditions (Jewkes and Moran, 2015). Currently, there is no systematic evidence monitoring the indoor temperatures inside prisons in the UK (Brown, 2017).

A number of prisons are at risk of flooding in England, Scotland, Wales and Northern Ireland although no recent published estimates are available. The 2008 National Flood Risk Assessment estimated that 13% of prisons are at risk of flooding (EA, 2009), and within London, three prisons are at risk of a 1 in 30-year flooding event and seven are vulnerable to a 1 in 100-year event (JCSC, 2019).

Evidence from the US highlights the impact of natural disasters on vulnerable and captive populations. Hurricane Katrina caused significant damage to US prisons in the exposed area, and inmates were without power, food, water for four days (Motanya and Valera, 2016). Heat-related deaths have also been reported in the US – 14 heat-related deaths and over 90 cases of heat-related illness or injury over 9 years in Texas, for instance (Motanya and Valera, 2016).

#### 5.14.1.2 Future risk (H13)

##### 5.14.1.2.1 Future risk: Education sector (H13)

Higher temperatures are likely to increase heat risks in the future, especially in the south of England, with London experiencing the highest levels of overheating (GLA, 2020). Projected electricity consumption by schools indicate that a cooling load under current weather conditions will be 25% of annual electricity consumption and 82% under predicted future conditions (Lykartsis *et al.*, 2017).

The CIBSE Schools Design Group on climate change adaptation made recommendations based on the modelled response of recently built schools in England to climate scenarios (Taylor *et al.*, 2020; Department for Education, 2020). The recommendations have informed the current ‘Specification 21’ rewrite of the DfE Generic Design Brief and Output Specification. Findings include:

- In a UK scenario consistent with 2°C global warming<sup>21</sup>, the overall number of classrooms not achieving current standards for thermal comfort is low.
- However, there are schools with substantial numbers of classrooms that do not meet the standards. The classrooms most at risk were found to be those with an increased exposure to solar gains – for example, south-facing, top-floor classrooms. Risks were higher in London and the south east of England, with dense urban areas also representing an increased risk because of the urban heat island effect.
- Conversely, there was some evidence that schools with higher standards of insulation and increased potential for ventilation in classrooms performed better.

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<sup>21</sup> 50<sup>th</sup> percentile of the UKCP09 projections with the SRES B1 emissions scenario in the 2080s. Projected changes in UK temperatures are around the upper end of the range for 2°C global warming in the UKCP18 derived projections (Gohar *et al.*, 2018)

- In a UK scenario consistent with 4°C global warming<sup>22</sup>, the majority of classrooms do not achieve the target comfort criteria, although impacts could be mitigated with effective design strategies such as cross-ventilation, thermal mass, high ceilings and room depth.

A significant number of schools are projected to be at increased risk of flooding in England, Scotland, Wales and Northern Ireland (Table 5.50). In scenarios of 2°C and 4°C global warming by 2100, the number of schools located in the highest all-cause flood probability category by 2080 is projected to increase by 32% and 95% respectively, assuming no change in adaptation or in the number of schools (Table 5.50). The Greater London Authority projected that schools in London will be at a high risk of surface water flooding in the future, especially during winter months. This risk is attributed to London's Victorian natural drainage systems and use of impermeable materials which exposes the city to a future risk of pluvial flooding. In London, 643 schools (22%) are estimated to be risk of a 1 in 30-year all-cause flood, and 781 (27%) are at risk from a 1 in 100-year all-cause flood (JCSC, 2019).

Table 5.50. Current and future flood risk for schools with different combinations of dates, climate pathways and population projections under the Reduced Whole System adaptation scenario: numbers of schools in probability band “significant”, all source flood type Source: Sayers <i>et al.</i> (2020a), see reference for further details.									
	Present (2020)	2050s				2080s			
Population projection		Low		High		Low		High	
Climate pathway (global warming reached in 2100)		2°C	4°C	2°C	4°C	2°C	4°C	2°C	4°C
ENGLAND (Total = 24,323)									
Schools	10710	14890	16780	15030	16934	16956	19816	17243	20168
NORTHERN IRELAND (Total = 1832)									
Schools	439	522	549	537	566	530	576	568	618
SCOTLAND (Total = 5046)									
Schools	387	551	584	560	591	574	597	587	612
WALES (Total = 1569)									
Schools	51	58	63	59	64	62	74	65	77

If any schools are exposed to risks from landslides or coal tip slope failures, we suggest that this risk may increase with more intense heavy precipitation projected in future (Chapter 1: Slingo, 2021).

#### 5.14.1.2.2 Future risk: Prison services

The Ministry of Justice have published Preparing for Climate Change: A Climate Change Adaptation Strategy, which highlights the key risks to prisons across the UK (Parry and Cole, 2020). Flooding,

<sup>22</sup> 50<sup>th</sup> percentile of the UKCP09 probabilistic projections with the A1FI emissions scenario in the 2080s (Murphy *et al.*, 2009). The projected changes in UK temperatures are within the upper end of the range for 4°C global warming in the UKCP18 derived projections (Gohar *et al.*, 2018).

storms and drought are indicated due to the risk of loss of building use and increased financial costs of repair or finding alternative accommodation for inmates. Overheating is a key risk to prisons as high temperatures impact the welfare of inmates, staff and visitors. The buildings may also not be usable, causing increased costs which compromise prison capacity. Unlike overheating, lack of heating (too cold rooms) is a breach of Health and Safety standards and also has been recognised as a problem in several prisons (Parry and Cole, 2020).

There is a risk to prisons from prisoner litigation following a climate hazard that is poorly managed (Jewkes and Moran, 2015). A consequence of more specific standards of prison environment legislation is it may give prisoners precedent to contest their safety within their cells and the indoor prison environment, hence why UK prison standards are currently so vague (Jewkes and Moran, 2015). Increased events of high ambient temperatures, especially during 23-hour lockdowns, may provide evidence of infringement of human rights.

#### 5.14.1.3 Lock-in and thresholds (H13)

There is considerable risk of lock-in for this risk because a significant part of the built environment in the UK is not adapted to future climates (CCC, 2019a).

It is important that new educational and justice buildings are designed appropriately for future climates to avoid lock-in. New buildings often have high levels of insulation and air tightness, low thermal mass and large glazing areas which can exacerbate heat risks if appropriate ventilation and passive cooling are not installed.

There are also lock-in risks for poor refurbishment and reuse of older buildings that do not adequately consider overheating and the nature of the existing building fabric and use. There are lock-in risks for urban areas that enhance rather than reduce urban heat islands (see Risk H1).

As discussed in Risk H1, heat responses are subject to a range of thresholds. Unlike lower temperature limits, there are no upper limits to how hot a classroom can be.

Lock-in will arise if development in flood risk areas is not resilient to current and future flood risk, and where flood risk management measures are currently, or will become, insufficient to manage the risk.

#### 5.14.1.4 Cross-cutting risks and Inter-dependencies (H13)

As the risks relate to risks from heatwaves and flood events, some of the evidence described in Risk H1 (higher temperatures), Risks H3/H4 (Flooding and coastal change) and Risk I8 (Risks to water supplies) are relevant here, particularly in relation to interventions in buildings and flood risk management policy.

Failures to adapt other sectors to flood risks can cause knock-on impacts. For example, a failure to address risks to infrastructure will have cascading social impacts, e.g. bridge closures could prevent



people getting to work or children to school. A combination of flooding and electricity failures can disrupt services to schools and prisons.

Climate change may also have an impact on historic and heritage sites (Risk H12) under the management of the MoJ including prisons, courts, probation facilities and memorial sites (MoJ, 2019b).

#### 5.14.1.5 Implications of Net Zero (H13)

As the UK Government has pledged to reach Net Zero by 2050, this may have implications for increasing the risk of overheating in buildings. The DfE 'Specification 21' will include requirements for achieving Net Zero Carbon schools in operation, and sets a framework for sustainability and embodied carbon in the new Sustainability Technical Annex.

New and retrofitted buildings, including educational facilities and prisons, will increasingly have energy efficiency measures integrated to align with the overall UK Net Zero objectives. These measures could have consequences for increased overheating in the summer due to increased air-tightness and reduce ventilation unless they are designed appropriately, with overheating and indoor air quality considered.

#### 5.14.1.6 Magnitude scores (H13)

<b>Table 5.51. Magnitude score risks to education and prison services</b>					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	Medium  (Medium confidence)	Medium  (Low confidence)	Medium  (Low confidence)	High  (Low confidence)	High  (Low confidence)
<b>Northern Ireland</b>	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Scotland</b>	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)
<b>Wales</b>	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)

The present day magnitude is medium in all countries (Table 5.51). For England, EAD from flooding to schools was estimated to be £12 million for lost school days after the 2007 floods, which justifies the medium score. Based on this evidence and studies on overheating in schools, the confidence score is medium for England. Our expert judgement is that similar (but relative) levels of flooding impacts could occur in the Das, therefore the scores are judged to be medium with a low confidence.

Our judgement is that for Northern Ireland, Scotland and Wales the scores remain medium in 2050 and 2080, with a low confidence reflecting the lack of evidence for both schools and prisons. There is little evidence of current or future impacts to prisons in England, although overheating risks are likely to become significant, after mid-century under high rates of warming and no adaptation. There are likely to be a large number of assets at risk of overheating and at risk from flooding, with a potentially large population affected in England by the 2080s. The scores for 2080 are therefore high with a low confidence.

## 5.14.2 Extent to which current adaptation will manage the risk (H13)

### 5.14.2.1 Effects of current adaptation policy and commitments on current and future risks (H13)

#### 5.14.2.1.1 Education

##### 5.14.2.1.1.1 UK-Wide

Education services in the UK are devolved, and specific policies for each UK nation are set out below.

Overheating in schools can be managed in part by operational measures, as often heat risks are caused by human behaviours such as using lights and electrical equipment, poor use of heating systems, heat build-up through the day not being released during the night and inadequate ventilation practices. Therefore, key practices that should be adopted include installation of automatic 'off' switches, isolating or re-locating heat sources, installing presence sensors for lighting, ensuring calibration of thermostats and sensors, and ensuring windows are accessible for opening and have sufficient night-time ventilation practices in place (especially given that it is probably impractical to leave windows open overnight due to security issues). Further measures that can be practiced by students and staff include dress code relaxation, regular hydration, encouraging of sun cream and hat use, limiting outdoor activity and using shade and regulating temperature through window ventilation and use of blinds. Schools need to develop plans for heat wave conditions to enable them to remain open. This could include the use of external shelters, fitting of shading devices, increased ventilation using forced draught ceiling fans and introducing earlier start and finish times.

Evidence indicates that schools are at risk of overheating and are likely to fail against overheating criteria without retrofit of significant adaptive measures (Lykartsis *et al.*, 2017; CIBSE, 2019).

Implementing and reliance upon cooling systems in schools will allow for thermal comfort, although at the cost of an increase in energy use (Lykartsis *et al.*, 2017; Teli *et al.*, 2017).

#### 5.14.2.1.1.2 England - Education

The Department for Education (DfE) has published revised guidelines on ventilation, thermal comfort and indoor air quality in new and refurbished schools. It sets out the regulatory framework and gives performance levels for compliance with UK regulations and further non-statutory guidance (Education and Skills Funding Agency, 2018).

DfE deals with overheating through revisions to Building Bulletin 101, which is quoted in Part F and L of the Building Regulations, and more frequent revisions to the current 'Output Specification' which is applied across all centrally-funded educational building programmes, in both new and refurbished schools. Ongoing revisions to Specification 21 and BB101 will be informed by the research carried out by the CIBSE Schools Design Group Climate Adaptation group (assessing both 2°C and 4°C warming scenarios) and other NERC and EPSRC funded research projects that are completed or ongoing (DfE, 2020). Specification 21 and Net Zero projects are addressing overheating in a proactive design process which aims to lead to a next generation of schools that do not overheat.

The cooling hierarchy given in Section 8.1.3 of Technical Annex 2F of the DfE Specification (DfE, 2020) advocates the use of passive measures before the use of mechanical cooling (DfE, 2020). There are many measures that can be implemented, such as shading and cross ventilation, before the use of mechanical cooling is required. If active cooling systems are needed, designers are required to ensure they are the lowest carbon options and that they are used for peak cooling but not full cooling.

In England, the Ministry of Housing, Communities and Local Government (MHCLG) published a consultation in 2021 proposing to introduce an overheating standard in new residential buildings, which includes residential educational settings (such as university halls of residence) as part of the Future Buildings Standard (MHCLG, 2021). If brought into policy this would likely help to tackle the risk of overheating in new residential educational buildings.

Local authorities are mindful of school estates meeting the highest standards of sustainable and environmental design set out in the Building Better Schools and Principle Six of the School Estate Strategy (LfS National Implementation Group, 2016). The Greater London Authority (GLA) has also recently released some guidance to support schools and academies adapt to climate change (GLA, 2020).

The recent understanding of the ventilation transmission route for COVID-19 has meant that ventilation design in schools is being re-evaluated by a number of groups from the risk perspective of the transmission of respiratory disease as well as for climate change adaptation risks including the risks of overheating and poor air quality from traffic and other pollution.

Recent policy announcements on flood risk management in England have included a focus on schools. The Government's revised funding formula for flood defence spending, announced in 2020,

includes new funding streams to protect critical infrastructure including schools (Defra, 2020b). There are many examples of local initiatives available for developing sustainable drainage systems on school estates, often led by local authorities. The GLA has developed a guidance document for London schools to manage flood risk (GLA, 2020). Additional operational changes are scarce in the context of reducing flood risk in schools, however regular maintenance of roofs, gutters and drains will promote drainage of rainfall, avoiding water pooling which may lead to damage. Additionally, schools are advised to raise equipment to be above flood level and where possible have backup power generation to prevent power outages (GLA, 2020).

#### 5.14.2.1.1.3 Northern Ireland - Education

The Education Authority in Northern Ireland has developed severe weather emergency guidance for schools. During periods of severe weather, it is important that schools take steps to minimise the potential impact on school buildings and facilities (EANI, 2019). The resources provide information about preventative measures that schools can take to minimise damage to the school estate in extreme weather conditions and how to protect school premises. The guidance is based on Met Office weather warning alert levels and gives information on the impact, likelihood and actions that the Education Authority and Schools should take in response to extreme weather events at each alert level.

#### 5.14.2.1.1.4 Scotland - Education

Scotland's Schools For the Future Programme will invest £2.8 billion in constructing, rebuilding and refurbishing over a hundred schools across Scotland (Scottish Government, 2019a). Scotland's Adaptation plan states that the schools programme will ensure that new and refurbished schools are fit for climate change, although there is little information on how this will be achieved.

#### 5.14.2.1.1.5 Wales - Education

Education Wales published a 21<sup>st</sup> Century Schools and Education Funding Programme Guide in 2018 to ensuring educational facilities are sustainable, which covers both mitigation and adaptation actions. The guide suggests useful references and examples for design teams and schools to consider when building new educational facilities or retrofitting existing buildings to ensure climate change readiness. The guide highlights four key risks to schools and colleges; overheating, water efficiency, construction and building fabric materials, and flooding. Advised overheating measures include using overheating assessment models that consider future climates and historic weather files as a standard design process. Design teams and developers must consider how to achieve adequate ventilation and avoidance of overheating through automation of windows, integration of CO<sub>2</sub> monitoring systems and mitigating heat gains, e.g. amount of people, lighting and IT equipment in classrooms. Funding requirements for the UK industry standard for assessment and certification, BREEAM (Building Research Establishment Environmental Assessment Methodology), request new educational projects to maximise water savings through the selection of water-efficient sanitary strategies and effective metering methods. During the assessment of new developments, it is important to consider the building materials selected for use in the construction of new schools, colleges and other educational facilities. These materials are required to be robust to withstand

heavier and more intense rainfall, higher wind speeds and other extreme events. The guide indicates that opportunities to maximise water attenuation on site should be discussed within project teams and integrate SuDS into plans.

The Eco-Schools programme has led to a number of adaptation benefits for schools in Wales. One example is highlighted as a case study in the Welsh Government's adaptation plan, Prosperity for All: A Climate Conscious Wales (2019). Rhyl High School in Denbighshire benefitted from funding to install Sustainable Urban Drainage. As well as protecting the school, the project also reduced the risk of flood to local homes in the area.

#### 5.14.2.1.2 Justice

##### 5.14.2.1.2.1 UK-Wide - Justice

The UK has three separate criminal justice systems: England and Wales (MoJ), Scotland (Justice Directorate and Scottish Prison Service), and Northern Ireland (DoJ). Adaptation strategies focus on ensuring buildings are fully functional and resilient to extreme weather.

BREEAM primarily assesses non-commercial building environmental credentials (NAO, 2017). It is a requisite for all newly built prisons to be awarded an excellent BREEAM ranking (NAO, 2017). This rating has been achieved in only one UK prison at time of writing (April 2020); HMP Thameside.

##### 5.14.2.1.2.2 England and Wales - Justice

Adaptation policy for prisons and court services in England and Wales is addressed by the Ministry of Justice, with overheating being a priority for action (Cole and Soroczynski, 2018). The MoJ's Estates Directorate are involved in research to combat solar gain, allowing prisoner control of cell temperature, considering solar power options and replacing poor building management systems (Cole and Soroczynski, 2018). The development of the Prison Estate Transformation Programme recognises the importance of climate resilience and incorporates this into the MoJ strategy (Cole and Soroczynski, 2018). A key consideration is the scope to mitigate flood risk, waste reduction, heating systems and to limit carbon emissions through building materials and design (Cole and Soroczynski, 2018).

MoJ requires all new buildings to be delivered to at least BREEAM Excellent standard and have explored whether achieving Outstanding is possible and cost-effective. This is set out in the MoJ BREEAM policy (MoJ, 2019a). The MoJ has reported some commitments already in action including reducing water consumption (Cole and Soroczynski, 2018; Cole, 2018).

The recent Ministry of Justice's Adaptation Strategy requires that sites assess risks using UKCP18 and use this assessment to inform adaptation plans/actions. A set of measures are recommended, but there is no analysis of costs and benefits (Parry and Cole, 2020). The strategy says that sites should:

- Build in more natural ventilation, solar shading and natural cooling.
- Improve Building Management System (BMS) controls.

- Have emergency plans in place that consider the likely intensity and frequency of heat.
- Deliver against objectives through an action plan to be used to monitor progress of initiatives and actively support the strategic objectives and continuous improvement throughout the estate.

Recent developments to flood and coastal erosion risk management policy for England and Wales, described above, should also include enhanced protection for prisons as critical infrastructure, though we have been unable to find specific quantitative information on the uptake of SuDS or other flood risk management measures.

#### 5.14.2.1.2.3 Northern Ireland - Justice

There is no current evidence of adaptation action for prison and justice services in Northern Ireland.

#### 5.14.2.1.2.4 Scotland - Justice

The Scottish Prison Service (SPS) does not currently have a policy and strategy to mitigate future climate-related risks in place (Scottish Prison Service, 2018). However, the SPS have reported that each prison has a dedicated waste recycling facility, including rainwater harvesting systems. Surface water source control from hardstandings is a key consideration for new or refurbished facilities and SPS design and construction project teams are required to consider design requirements for the safe removal of surface water from buildings, without damage to the buildings or to people around the building, and without posing a risk to the environment by flooding or pollution. SPS design and construction project teams must also consider the use of more sustainable, permeable design options and ensure that surface water runoff to ground utilising a sustainable urban drainage system (SuDS) authorised by SEPA.

#### 5.14.2.2 Adaptation shortfall (H13)

There is evidence of planning and guidance in line with scenarios of 2°C and 4°C global warming by 2100 being developed in England and Wales, for both education and justice. Education policy in Scotland and Northern Ireland also makes reference to the need for adaptation of schools and other facilities, though the specific requirements appear from the evidence above to be more general. There is less evidence available for planning for a range of climate scenarios and hazards in the justice sector in Scotland and Northern Ireland.

Further adaptation measures are likely to be needed in each nation to avoid lock-in with building designs, in particularly new or refurbished buildings and adapt to the future risks of overheating, flooding and other climate hazards.

There is a shortfall in adaptation planning in relation to prison guard occupational health, inmate safety and building resilience to climate risks, especially for Northern Ireland and Scotland. The prison population is ageing, and this is likely to exacerbate the impact of extreme weather in the future (Motanya and Valera, 2016).

### 5.14.2.3 Adaptation Scores (H13)

These adaptation scores take into account plans and policies in place for both education and justice services for overheating and flood risk. In general, there is a lack of evidence of specific policy in both sectors in Scotland and Northern Ireland. There are policies and guidance in place in England and Wales to address overheating in schools and prisons, which account for high climate scenarios, but these may not be enough to fully address future risks under climate change. There is less evidence of specific policies to manage future flood risk, though new strategies for flood and coastal erosion risk management should include enhanced measures for critical infrastructure, including in the education and justice sectors.

**Table 5.52.** Adaptation scores risks to education and prison services

Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (High confidence)	No (Low confidence)	No (Low confidence)	Partially (High confidence)

### 5.14.3 Benefits of further adaptation action in the next five years (H13)

#### 5.14.3.1 Education (H13)

Across the education system, many schools are limited in their resources, are older buildings, and staff lack sufficient knowledge, hindering effective climate adaptation planning to respond to and recover from extreme events. The general set of adaptation interventions for schools are similar to other buildings, although there are additional low regret options for behavioural responses and emergency plans. There is some specific information on potential options and general affordability (e.g. GLA (2020)), as well as potential benefits (noting these include reduced cognitive and learning issues, mental health, and lost school days). Thompson *et al.* (2015) report on several projects under the Innovate UK's Design for Future Climate, Adapting Buildings (D4FC) programme, which included schools, with reported costs for adaptation measures. There is also some international literature which identifies the benefit to cost ratios for greening schools (Kats, 2003, 2006; Zhang *et al.*, 2018) which report higher costs, but net benefits when considered on a life cycle basis. However, costs and benefits vary on a case-by-case basis, and between retrofits and new buildings.

Further adaptation measures are essential to avoid lock-in with building designs and adapt to the future risks of overheating, flooding and other climate hazards. Importantly, the first step for adaptation is developing a school climate adaptation plan with specific targets, strategies, tasks and roles to ensure its delivery and effectiveness. This plan must be centred to ensuring child health and wellbeing, thus engagement across the whole school system, including school decision makers and external support is necessary with the aim to increase the school's adaptive capacity. A whole school approach is desired to reach optimal effectiveness, considering positive and negative measures and how they interact, but also how this plan integrates with the wider school agenda. Having a school

climate adaptation plan delivers multiple positive outcomes including reduced bills, increased learning opportunities, improved biodiversity and better air quality.

A variety of adaptation measures targeted at school buildings have also been proposed by the Greater London Authority that are specific to London Schools, but are likely relevant to the UK-wide context (GLA, 2020). These include multiple modifications to roofs such as green or blue roofs and cool roofs which are reflective or light in colour. As overheating is increasingly becoming a high risk to schools, many measures suggested are around cooling technologies and ventilation. Examples of these systems include windcatchers – natural ventilation systems harnessing wind blowing to ventilate indoor areas – automated window ventilation, hybrid natural and mechanical ventilation, and mechanical cooling or air movement (air conditioning). Additional measures to manage heat risks include thermal massing and solar shading – interception of sunlight to reduce heat entering buildings.

Many measures have been proposed as effective adaptive strategies for school outdoor grounds across different space requirements and resource availabilities (GLA, 2020). For schools with limited space availability, rain planters and gardens, tree and shade structures, drain filters and permeable or green surfaces are effective ways to manage heat, flood and water scarcity risks through increasing shade, water availability, biodiversity and promoting draining of excess water. Additionally, schools with more space availability can install or adopt below- or above-ground rainwater attenuation tanks and ponds to store excess rainwater and potentially regulate local temperature, reducing the urban heat effect. Furthermore, some measures require a large area, thus schools with the available space can implement a swale – a shallow ditch to store, transport and absorb run-off – or a basin – a shallow depression in the ground covered in grasses to capture water, reducing run off.

Schools should also consider ways to reduce the risk of water shortages by limiting their reliance on the mains water supply (see Risk 18 in Chapter 4: Jaroszweski, Wood and Chapman, 2021). To reduce water use, schools can install tap aerators and low flow taps which reduce flow of water through taps by up to 50%; also dual flush toilets allow two available flush volumes, reducing water consumption. Furthermore, reducing usage through behavioural changes to minimise consumption and wastage will have a positive impact on London's water supply. Additional building modifications include increasing the permeability of surfaces to replenish the water table, which has added benefits for reducing flood risk and harvesting rainwater for non-drinking purposes (GLA, 2020).

#### 5.14.3.2 Justice Services

There are a set of similar adaptation options for prisons as for schools, both non-technical and technical, with similar types of issues, i.e. building heterogeneity, and whether a scheme is retrofit versus new. The recent Ministry of Justice's Climate Change Adaptation Strategy (Parry and Cole, 2020) requires that sites assess risks and use this assessment to inform adaptation plans/actions, and a set of measures are recommended, but there is no analysis of costs and benefits. There is some information (Jewkes and Moran, 2015) on recently completed prison projects which are designed to meet the BREEAM Excellent standard and include some relevant information of practical examples of adaptation.



### 5.14.3.3 Overall urgency Scores (H13)

This is a new risk that was not considered in previous UK climate change risk assessments. The scores have been judged as more action needed. In England and Wales, as discussed above policies and guidance are in place for overheating. Further evidence of these reducing vulnerability is needed. Policies are in place to address flood risk for critical infrastructure, but there is a lack of evidence on how well education and justice buildings and land are being protected compared to the rising risk. In Scotland and Northern Ireland more action is needed for both education and justice buildings on flood risk and overheating.

<b>Table 5.53. Urgency scores for risks to education and prison services</b>				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Low	Low	Medium

### 5.14.4 Looking ahead (H13)

Further evidence is needed to understand the health impacts climate change will have on schools and prisons. Furthermore, indicators need to be developed to assess the impact overheating has on children in schools, as well as inmates in prisons. Building standards must include regulations for appropriate ventilation and adaptive measures as well as appropriate energy efficiency strategies.

## 5.15 Challenges to adaptation

Many of the challenges to adaptation that were identified in the previous risk assessment remain (Kovats and Osborn, 2017). This section summarises the key barriers to adaptation across the risks discussed in this chapter and addresses two key policy areas where action has been limited (planning and housing policy).

There are several barriers that may become more significant in the future. The evidence presented in this chapter for all 13 risks to health and wellbeing suggests that adaptation to current climate risks is currently limited by:

- Limited incorporation of the full scope of planning policy and its means of implementation in local planning processes and construction practices in new developments. (See section on planning below).
- Fragmentation of services both locally (with local agenda-setting priorities), and also fragmentation across sectors. This is particularly relevant for adaptation in the health and social care system.

- In some areas, governance structures are not sufficient to address climate change risks, for example for communities threatened by sea level rise.
- Lack of economic studies to demonstrate the cost-effectiveness of adaptation options and with due consideration of environmental, health and social co-benefits.
- Lack of understanding when sustainability thresholds or capacities have been exceeded.
- The lack of action in building standards, housing design, performance and construction remain. Although steps have been taken to try to address these gaps, these have not been completed at the time of writing (see housing section below).
- The lack of incentives for retrofitting existing properties (see housing section below).
- Lack of monitoring of appropriate indicators that reflect climate risks to health and public health actions.
- Climate change policies for mitigation. For some risks, policies to achieve Net Zero may undermine adaptation strategies or make them harder to achieve. However, there are also synergies, where adaptation and mitigation goals can be addressed at the same time (see Net Zero section below).

Lock-in is a key concern for our capacity to adapt to future climate risks. Future adaptation to climate risks will be limited by lock-in, which is described in relation to each risk. In addition, adaptation will be limited by:

- Organisational and systemic factors that inhibit adaptation and flexible decision making. Further fragmentation of services in the public sector and in health and social care systems will also impede adaptation.
- Despite clear national and local policies on green infrastructure (nature-based) solutions there are barriers to implementation (discussed in more detail in Chapter 3: Berry and Brown, 2021).
- Housing and planning policies that do not sufficiently consider climate adaptation and the health and well-being of occupants (see sections below).
- Building in flood zones as flood risk increases as a result of climate change and is not sufficiently resilient to changing risk. A spatial shift in flood zones as a result of climate change could result in more homes built over the last decade ending up in higher flood zones over their lifetime without further mitigating action.
- Lack of implementation of strategies that require changes in behaviour. Especially the low uptake of adaptation strategies by households (e.g. retrofitting and Property Flood Resilience, PFR). There is good evidence that the level of understanding of current risks by individuals is low in the general population and those at high risk.

There are some risks that are beyond the limits of adaptation. These include major climate events, and the Low Probability High Impact events described in Chapter 1 (Slingo, 2021) and Box 5.1.

Investment in EPRR (emergency planning, preparedness and response) is an important part of addressing climate hazards. Under the Civil Contingencies Act, local authority emergency planners and frontline agencies produce and update the Community Risk Register and plans to respond to a series of events including severe weather (including heatwaves and flooding), pollution events,

pandemics and other serious incidents. Climate change as a long-term challenge is not included within the responsibilities of the Civil Contingencies Act, which is predominantly focused on response to individual incidents that may occur in the near future. At present they do not focus on increasing climate risk over the long term, but could offer insight in responses, resilience, and the scale and nature of climate risks.

### 5.15.1 Evidence for adaptation at local level

Local authority action on climate change has increased in recent years. Approximately 70% (of all District, County, Unitary & Metropolitan Councils have declared a climate emergency in the UK<sup>23</sup>. The 2019 UK City leaders' Survey indicated that a top spending priority was climate change mitigation (Neuhuber *et al.*, 2019). However, climate emergencies tend to focus on Net Zero, often with supporting routemaps to reduce emissions; adaptation is rarely considered. This is a wider issue as policy makers tend to focus on one side of the coin, either adaptation or carbon reduction, whereas the real win-win solutions will be achieved by addressing both.

Adaptation actions are within the remits of a wide range of departments within local government and other agencies that operate at the local level (planning, water resources, flood management, agriculture, energy, transport, environment, and public health). The siloed approach can be a barrier to action as there is often no clear lead agency to promote adaptation responses (Lorenz *et al.*, 2019).

Evidence is limited on the implementation of adaptation actions. Local adaptation is primarily at the planning and implementation stage, with raising awareness being the common priority (Lorenz *et al.*, 2019). Surveys of local authority environmental officers found that local governments were 'thinking about climate change adaptation' (Ipsos MORI, 2010; Porter *et al.*, 2015). Public health consultants within local authorities did not have explicit remits or approaches for climate adaptation strategies however; often action followed public health's emergency planning functions (Woodhall *et al.*, 2019).

A report from the Committee on Climate Change (2015) stated that from a survey of 90 local authorities, 40% have a published adaptation strategy (JBA, 2015). Furthermore, nearly a third more were in the process of developing a plan or could refer to their County Council strategy. Primarily, adaptation plans focused on raising awareness and staff training, although some specific actions were highlighted, including sustainable drainage systems, water efficiency, passive cooling and green infrastructure (JBA, 2015). In 2017, this report was updated; support from central government had diminished and local government progress was limited (CCC, 2017). Current and future funding from central government being marginalised has led to closure of the Environment Agency's Climate Ready Support Service, the Local Government Association's 'Climate Local' initiative, Climate UK and over half of UK regional climate change partnerships (CCC, 2017). A key message highlighted was that due to the departure from the European Union, local authorities will not have access to EU funding and resources such as the European Structural and Investment Funds (CCC, 2017).

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<sup>23</sup> <https://www.climateemergency.uk/>

The Environmental Audit Committee also noted the lack of action at local authority level and recommended that Defra does more to monitor progress in adaptation and also ensure that adaptation guidance for local authorities is updated regularly. As the risks from climate change grow, funding for Regional Climate Change Partnerships should be reinstated (Environmental Audit Committee, 2018b, paragraph 45).

Despite no mandatory policy for health systems to develop mitigation and adaptation policy (except in Scotland where public bodies are required to report on adaptation), a variety of national initiatives (NAP, SDU, PHE, Environment Agency) are encouraging climate action in the local health and social care sector. A survey of 152 areas was conducted by the Environment Agency, of which 29 boards responded (CCC, 2015). 18 of the 29 boards (strongly) agreed that plans were in place to address negative impacts to health from extreme weather and climate change (CCC, 2015). A systematic review of policy documents highlighted that adaptation plans were more prominent in the health sector in the final quarter of 2013–2015 and that increased political support for CCA can have a significant impact on sector funding and resource allocation (Lorenz *et al.*, 2019).

A report from the WHO highlighted how CCA policies in 20 EU countries impact public health, and reported that 65% had a specific climate change and health programme (WHO, 2018b). Additionally, 90% ensured that health was represented in all climate change action/processes (WHO, 2018b). European public health systems have strengthened to cope with the impacts of climate change through improving early warning systems, addressing vulnerable populations and strengthening infectious disease surveillance. A European Environment Agency (EEA) survey of the 32 member countries in the European Economic Area indicated most were in either the formulation (10/30) or the implementation (9/30) stage with few at the monitoring and evaluation stage. All responding countries reported to be at least at the agenda-setting phase of their climate change adaptation plan (EEA, 2014).

### 5.15.2 Adaptation through the planning system

The planning system in the UK is fully devolved (Table 5.54). The planning system is relevant for risks that are mediated by the built environment, including flooding (H3, H4), heat (H1, H2, H6), air quality (H7), and building fabric (H6).

- National Planning policies in England and Northern Ireland state that plans must ‘include policies designed to secure that the development and use of land in the local planning authority's area contribute to the mitigation of, and adaptation to, climate change’. The Planning Practice Guidance (PPG) indicates that this will be a consideration when plans are examined, therefore it is important that thought is given to this matter within local plans.
- Northern Ireland is developing a new Housing Strategy that will set out targets for new homes. The NI Strategic Planning Policy Statement states that ‘the planning system should help to mitigate and adapt to climate change’. However, there is little evidence regarding specific actions for managing heat risks (indoor or outdoor).
- The Planning (Scotland) Act 2019 makes the future National Planning Frameworks part of the development plan for day to day decision making purposes. The 2019 Act also sets out a range of policy and strategy which needs to be considered in the preparation of the National Planning Framework, and includes ‘the programme for adaptation to climate change

prepared under section 53 of the Climate Change (Scotland) Act 2009'; i.e. the Scottish Climate Change Adaptation Programme. As such for Scotland, the planning system role in adaptation has been strengthened for future iterations of national policy. The next National Planning Framework (no. 4) is already in preparation and due in draft form in Autumn 2021.

- The Future Wales: National Plan 2040 (2021) is Wales' national development framework, setting the direction for development. It is a plan with a strategy for addressing key national priorities through the planning system, including climate resilience and achieving decarbonisation. Planning Policy Wales (Edition 11, 2021) includes policies that contribute towards climate change mitigation and adaptation. For adaptation, these include the location of new development, the design of buildings, the strategic importance of green spaces and the Welsh government's approach to managing development in areas of flood risk. It is supplemented by a series of Technical Advice Notes (TANs), Welsh Government Circulars, and policy clarification letters which together with the PPW provide the national planning policy framework for Wales.

**Table 5.54. Planning guidance for adaptation**

Country	Current policy and guidance	Evidence for planning in managing flood risks	Evidence for planning in managing heat risks
England	<ul style="list-style-type: none"> <li>• National Planning Policy Framework</li> <li>• Planning Practice Guidance for climate change and flood risk and coastal change</li> </ul>	9% of planning permissions granted for properties on the flood plain; these should have requirements that resilience measures are incorporated but there is no monitoring evidence as to whether this is achieved. All policies focus on directing development away from the flood plain. SuDS are discretionary not mandatory.	Some evidence at a city level especially for London. Focus on green infrastructure in Birmingham, Manchester and other cities.
Northern Ireland	<ul style="list-style-type: none"> <li>• Regional Development Strategy 2035</li> <li>• Strategic Planning Policy Statement</li> </ul>	No data available for properties granted planning permission on the flood plain. All policies focus on directing development away from the flood plain. SuDS are discretionary not mandatory.	
Scotland	<ul style="list-style-type: none"> <li>• National Planning Framework 3</li> <li>• Scottish Planning Policy</li> <li>• Planning Advice Notes</li> </ul>	No data available for properties granted planning permission on the flood plain. All policies focus on directing development away from the flood plain. SuDS are discretionary not mandatory.	
Wales	<ul style="list-style-type: none"> <li>• Planning Policy Wales (Edition 10) Technical advice notes</li> </ul>	No data available for properties granted planning permission on the flood plain. All policies focus on directing development away from the flood plain. SuDS are mandatory.	

Planning policies do permit development in areas at risk of flooding providing floor levels are raised, and/or household resistance or resilience measures are incorporated (see discussion in H3). Housing development continues to occur on the flood plain (MHCLG, 2020). Whilst climate resilient homes can be built on the flood plain, either with community level defences in place or with PFR measures, further evidence regarding the degree to which resilient measures are being incorporated is required. Planning applications for development in areas at risk of flooding need to be supported by independent evidence that flood risk from all sources, including surface water and taking account of the implications of climate change, has been assessed and mitigated. The proportion of planning decisions made against advice remains very low.

There is little evidence so far that adaptation (heat risks) has been taken into account in planning decisions, and based on internal analysis by the CCC (as discussed in the CCC's 2021 Progress Report) it is not clear if Local Plans are incorporating overheating in terms of building design and layout.

The planning system in England is subject to change. In 2020, the Government published a White Paper to consult on proposals to reform the planning system.

### 5.15.3 Adaptation through housing policy

Adaptation is inextricably linked to wider government objectives about the built environment, in particular climate change mitigation. The specific risks above describe these issues for planning and design in relation to overheating, flooding, household energy, subsidence, wind damage and damp, cold homes.

As with planning policies, UK housing policies and regulations are devolved. The current regulations relating to thermal efficiency, overheating, air quality and moisture penetration are set out in Building Regulations and Standards for new homes and refurbishments. There are also a range of wider regulations, standards and guidance documents that are relevant.

There is likely to be significant house building undertaken in the next few decades in order to meet government targets for new homes (see section 5.1.3). These homes will be built to current regulations and may therefore need to be retrofitted in the future in order to meet Net Zero targets and ensure thermal comfort, good levels of indoor air quality for occupants and property level flood resilience. New and existing homes also often do not perform in line with minimum standards of performance expected by law due to issues with knowledge, skills, supply chains, occupant behaviour and quality assurance. Failure to perform in line with standards means locking in homes with risks to health from heat and cold, potentially higher costs to household for damage or energy costs, and greater risks of flooding (CCC, 2019a). Improving Building Regulations, that take a 'whole-building' approach to energy efficiency, ventilation and overheating, and ensuring compliance against standards is the best option to reduce future risks to health and wellbeing in new builds (CCC, 2019a).

In England, the Government plans to introduce a Future Homes Standard by 2025, so that new build homes are future-proofed with low-carbon heating and high levels of energy efficiency. A consultation published by MHCLG in January 2021 sets out plans to incorporate an overheating

standard into Building Regulations to be introduced alongside the Future Homes Standard. The consultation proposes to introduce a new regulatory requirement for overheating mitigation, alongside consideration of usability and new statutory guidance for occupiers (for energy efficiency, ventilation, and overheating), with the aim of reducing overheating risk in new-build residential buildings.

Reduced fuel poverty and improved health are major benefits associated with the energy efficiency programmes undertaken by UK and Devolved Governments. The UK Clean Growth Strategy (2017) highlights the need to improve the energy efficiency of our homes with the aspiration for all homes to be of an Energy Performance Certificate (EPC) Band C standard by 2035 (HM Government, 2017). The Sixth Carbon Budget pathways take into account the need to look at ventilation and passive cooling alongside energy efficiency in retrofits. However, current policies to reduce the carbon emissions of the housing stock could result in some unintended consequences (CCC, 2019a). Energy efficiency measures such as insulation can make homes more air-tight, which has implications for overheating (see Risk H1), moisture (see Risk H5) and indoor air quality (see Risk H7). A more integrated approach to decision-making and incentives for retrofitting adaptation measures could help to ensure that direct benefits and co-benefits can be optimised and made more explicit.

Occupant behaviours are also key for developing robust adaptation and mitigation strategies (McGill *et al.*, 2015; ZCH, 2016; Palmer and Walls, 2017). There is a lack of information on how people can operate existing buildings effectively, or guidance on what adaptation measures can be done to their home. For example, barriers to PFR installation (Risk H3) include lack of motivation from householders, lack of familiarity and access to information, costs and behavioural biases to taking action, and lack of professional skills and knowledge (CCC, 2019a).

#### 5.15.4 Net Zero: interactions between mitigation and adaptation

Adaptation to climate change needs to be considered in the context of the major policy and other changes that are needed to meet the Net Zero target of the UK Government (Priestley *et al.*, 2019). The main sectors for action related to housing, household energy, agriculture and food systems.

There is great potential to benefit health and wellbeing through Net Zero Pathways, and these have been discussed in detail within each risk. The benefits from reduction in outdoor air pollution are potentially large. Williams *et al.* (2018) modelled reductions in ozone and PM2.5 in urban areas associated with UK low carbon policies. There are also significant health and economic benefits from homes adapted to cold weather, active travel and diets low in animal products.

Key issues where there is a synergy or conflict with adaptation and mitigation objectives are summarised in Table 5.55. This table summarises the information already discussed in the individual risks.

<b>Table 5.55. Summary of risks where adaptation is likely to be affected by Net Zero objectives</b>			
<b>CCRA3 Risk/opportunity</b>	<b>Net Zero objective</b>	<b>Comments</b>	<b>Key current plans and policies to address Net Zero objectives at a national level</b>
H1: Risk to health and wellbeing from high temperatures	<ul style="list-style-type: none"> <li>• Increase in energy efficiency in buildings</li> <li>• Increase in low-carbon heating systems</li> </ul>	<ul style="list-style-type: none"> <li>• High levels of insulation installed in new and existing homes can increase risk of overheating if appropriate adaptation measures are not implemented.</li> </ul>	<ul style="list-style-type: none"> <li>• Energy Company Obligation</li> <li>• Renewable Heat Incentive</li> <li>• Scotland's Energy Efficient Strategy</li> <li>• Prosperity for All: A Low Carbon Wales</li> <li>• Northern Ireland Sustainability Energy Programme</li> <li>• Review of Part L of Building Regulations (England and Wales)</li> </ul>
H3: Risks from flooding	<ul style="list-style-type: none"> <li>• Not specific to flooding in the context of health</li> </ul>	<ul style="list-style-type: none"> <li>• Flood defences have high embodied carbon.</li> <li>• Natural Flood Management (NFM) has the potential to sequester substantial amounts of carbon, particularly if undertaken on a large scale involving woodland planting, soil carbon improvements and land use change.</li> </ul>	<ul style="list-style-type: none"> <li>• Carbon Planning Tool (Environment Agency) and similar tools under development in Scotland and Wales.</li> <li>• Nature-based solutions for carbon capture.</li> </ul>
H5: Risks to building fabric	<ul style="list-style-type: none"> <li>• Increase in energy efficiency in buildings</li> </ul>	<ul style="list-style-type: none"> <li>• High levels of energy efficiency in new and existing homes can increase the airtightness of the building. This can increase the risk of damp and mould growth.</li> <li>• Increased energy efficiency could reduce the burden of disease due to cold homes.</li> </ul>	As Risk H1
H6: Risk from changing energy demand	<ul style="list-style-type: none"> <li>• Increase in energy efficiency in buildings</li> <li>• Increase in low-carbon heating systems</li> </ul>	<ul style="list-style-type: none"> <li>• Net Zero objectives will affect energy technology, fuel choice, energy efficiency depending how it is met. The focus should be on designing energy systems for a changing climate, including both future heating and future cooling demand.</li> <li>• Passive measures for space cooling would reduce summer demands for energy.</li> </ul>	As Risk H1
H7: Air quality	<ul style="list-style-type: none"> <li>• Reduce emissions for energy production, industry and transport</li> <li>• Increase in energy efficiency in buildings</li> </ul>	<ul style="list-style-type: none"> <li>• Reducing emissions will improve outdoor air quality and reduce the impact of future climate exacerbating poor air quality.</li> <li>• High levels of energy efficiency in new and existing homes can increase the airtightness</li> </ul>	<ul style="list-style-type: none"> <li>• Clean Growth Strategy (2019)</li> <li>• 25 Year Environment Plan</li> <li>• As Risk H1 for indoor air quality</li> <li>• Review of Building Regulations Part F (England and Wales)</li> </ul>



		of the building. This can increase exposure to indoor air pollutants if appropriate ventilation measures are not implemented.	
H9: Food safety and food security	<ul style="list-style-type: none"> <li>Changes in land use and food production</li> <li>Changes in food consumption (types of food, sources of food)</li> </ul>	<ul style="list-style-type: none"> <li>Food safety risks may change, especially as animal products are more prone to contamination.</li> <li>Reductions from less meat in diet, or increased contamination by pesticides (for increased local production). UK's future trade relationship with EU may result in increased dependence on domestic food supply.</li> <li>Health benefits from diets low in animal fat.</li> </ul>	<ul style="list-style-type: none"> <li>Agriculture Bill</li> <li>Environment Bill</li> <li>National Food Strategy</li> <li>Fisheries Bill</li> <li>25 Year Environment Plan</li> </ul>
H11: Risk to cultural heritage	<ul style="list-style-type: none"> <li>Increase in energy efficiency in buildings</li> <li>Reduce emissions for energy production, industry and transport</li> </ul>	<ul style="list-style-type: none"> <li>High levels of insulation and energy efficiency installed in historic buildings can increase risk of overheating, damp and mould growth, and poor indoor air quality due to increased air tightness if appropriate adaptation measures are not implemented.</li> <li>Reduction in emissions should lead to less NO<sub>x</sub> and CO<sub>2</sub> being emitted in cities, which can become acidic and corrode/discolour buildings.</li> </ul>	<ul style="list-style-type: none"> <li>Clean Growth Strategy (2019)</li> <li>The Assessment of Energy Performance of Non-Domestic Buildings (Scotland) Regulations 2016</li> </ul>
H12: Risks to health and social care delivery	<ul style="list-style-type: none"> <li>Reduce carbon emissions associated with buildings (energy efficiency), travel and products (e.g. pharmaceuticals).</li> </ul>	<ul style="list-style-type: none"> <li>Restrictions on air conditioning and space cooling measures.</li> <li>Same as H1 and H5.</li> </ul>	<ul style="list-style-type: none"> <li>NHS England Net Zero plan</li> <li>NHS Long Term Plan</li> <li>NHS Green Plans</li> <li>Sustainable Development Strategy for NHS Scotland</li> <li>Carbon Neutral Public Sector 2030 target (Wales)</li> </ul>
H13: Risks to education and prison services	<ul style="list-style-type: none"> <li>Reduce carbon emissions associated with buildings (energy efficiency) and travel</li> </ul>	<ul style="list-style-type: none"> <li>Restrictions on air conditioning and space cooling measures.</li> <li>Same as H1 and H5.</li> </ul>	<ul style="list-style-type: none"> <li>Carbon Neutral Public Sector 2030 target (Wales)</li> </ul>

### 5.15.5 COVID-19 pandemic and response: implications for adaptation in the UK

The COVID-19 pandemic has resulted in significant impacts on the UK population, as well as changes in policy and policy structures. The implications of the pandemic and responses (including lockdown and social distancing) have been described in individual risks where relevant. These are also summarised in Table 5.56. There are likely to be long term consequences of the COVID-19 pandemic that will have important implications for adaptation, particularly in the health and social care sector.

More positively, the impacts of COVID-19 may have raised awareness of the importance of understanding major threats that can disrupt lives and livelihoods including low probability, high impact events. The pandemic may also lead to a renewed focus on reducing health and social inequalities.

**Table 5.56.** Implications of COVID-19 for managing climate risks

CCRA3 Risk	Risk Management	Observed impacts
Heat and indoor air quality – H1, H7	<p>Guidance on shielding, social distancing and lock downs may lead to more people staying indoors during hot weather, therefore exposed to high indoor temperatures and poor indoor air quality, particular for high risk individuals.</p> <p>Significant shift to home working may increase exposure to high indoor temperatures and non-optimal thermal comfort and air quality.</p>	Impact of 2020 on mortality heatwave was much higher than in previous heatwaves (PHE, 2020b)
Flooding – H3	<p>Evacuation due to flood and storm events can increase the risk of exposure to COVID-19, as social distancing is not possible.</p> <p>Mental health risks from flooding may be exacerbated during the pandemic, particularly if people have to leave their homes.</p>	Gaps in response to floods
Emergency planning – H1, H2, H3, H4, H12, H13	<p>Pandemic has revealed some gaps in emergency planning response.</p> <p>Emergency planning has also been limited by resources and persons being diverted to pandemic response at LA and national level.</p>	Gaps in response to floods in Jan/Feb 2021 due to pressures on emergency services and health services.
Inequalities in climate risks, esp. food poverty, energy poverty – H6, H9	<p>Economic impacts of the pandemic have led to decreases in household income.</p> <p>Renewed focus on health inequalities.</p>	Reported increase in food poverty in 2020 (Loopstra, 2020; Environmental Audit Committee, 2020a)
Public health response – H1, H2, H3, H4, H7, H8, H9, H12, H13	<p>Health bodies have seen a redeployment of staff to deal with the pandemic response. This may have affected progress in other areas of work, including climate change.</p> <p>The migration of PHE into the UK Health Security Agency (UKHSA) may disrupt programmes and relationships in the short-term due to organisational change, and in the longer term the priorities of UKHSA may be different thus reducing capacity and capability to address adaptation to climate risks.</p>	Reorganisation of public health services and financial pressure on local authorities may lead to reduction in focus of health improvement measures (Rimmer, 2020)
Cultural heritage – H11	Loss of revenue (due to lockdown and other measures) likely to reduce some options for adaptation.	

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UK Climate Risk  
Independent  
Assessment (CCRA3)

# Technical Report

## Chapter 6: Business and Industry

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## Key Messages

### What are the risks today and in the future?

- None of the current and future risks to business from climate change identified in the second Climate Change Risk Assessment (CCRA2) have decreased in magnitude. This partly reflects an improved ability to assess and report these risks, but it also reflects that business decisions continue to create additional risk by locking in increased exposure and vulnerability.
- Confidence in risk assessments is growing with better quality analysis and more sophisticated analytical approaches emerging, but limitations still exist. For example, it is often unclear if and how risks with low likelihood and high impact indirect risks and interdependencies are being considered by businesses. There is a lack of focus in particular on quantifying indirect losses, despite these potentially having significant implications for different business functions (in particular for B1, B2).
- Business and industry are exposed to threshold effects beyond which there is a step-change in risks, and which may necessitate much greater levels or different types of adaptation. This can be in the context of biophysical, engineering or policy thresholds. For example, increased demand for agricultural products or tourism services are subject to temperature thresholds and are likely to only occur for a specific duration. Another threshold is insurability – once reached this is expected to lead to a significant increase in magnitude of risk. These thresholds are likely to vary by time and place depending on the state of the assets, levels of investment to address climate change risks and/or maintain or improve the state of the assets, and the changing level of risk spatially over time (see B4, B5).
- A further concern are lock-ins that occur when business decisions ‘lock in’ future climate risk that may be irreversible or costly to revert later. There is evidence of lock-in through risk-insensitive behaviour. This can occur through businesses’ decisions on operating models, site locations, infrastructure, supply chains, technologies, policies, or pre-existing adaptation actions, which may increase exposure to long-term risks. Lock-ins are concerning when they result in higher magnitude of risk due to slow adaptation or mal-adaptive response (B1, B2, B3, B6).
- Cross-cutting risks: Physical climate risks and their impact on businesses in the UK are highly interdependent and there are a range of cross-cutting aspects that are relevant to Chapter 6 but covered elsewhere in the CCRA3 Technical Report, which are outlined in Section 6.1.4. These include cross-cutting risks with the natural environment and assets, infrastructure, people and the built environment, and international dimensions of climate risk.
- The focus in this chapter is on domestic (from climate change in the UK) risks. However, a key source of risk for many UK businesses is the result of climate change outside the UK which affects UK businesses through investments, supply chains, distribution networks and other business relationships. Climate change outside the UK may further affect UK

businesses through its impact on production and comparative advantage, and thus trade. While there are some mechanisms to monitor and address these risks - such as interdependencies mapping, supply chain resilience and trade agreements - the extent of these risks relies heavily on the extent of adaptation action outside the UK. Chapter 7 (Challinor and Benton, 2021) explores international risk in more detail – although it is referenced in this chapter where relevant. The urgency scoring in this chapter relates to domestically driven risks only.

#### What are the opportunities today and in the future?

- The changing climate can bring opportunities to some sectors and localities through shifting demand patterns leading to new markets for goods and services, better growing conditions or an increased need for financial solutions (see in particular B7).
- There are some early indications that some businesses are looking at potential opportunities from climate change, with some examples for goods and for services, but consideration of possible benefits remains largely unexplored (B7).
- Net-zero carbon strategies and the implications of these for adaptation as well as the embedded carbon of some adaptation measures such as air conditioning or flood barriers have not yet been assessed in a systematic way (B1, B2, B5).

#### Are the risks being managed, taking account of government and other action?

- Evidence of corporate adaptation action remains low. As in CCRA2, this can be viewed as a risk, and limits the ability to indicate the scale of the adaptation shortfall (or adaptation gap) and inform further benefits of adaptation.
- Overall awareness of adaptation as a business issue is low compared to awareness of mitigation and in many instances, businesses confuse mitigation measures for adaptation (see B4).
- Adaptation actions vary across businesses depending on company size, sector, location, past experience, access to information and resources, extent of a public-facing customer base, policy and regulatory frameworks in place, stakeholder and shareholder expectations, risk management processes, competitive advantage and company culture (B1, B2, B3, B4).
- There is little evidence that the growing awareness of climate risks (and their disclosure) has led to changes in investment decisions. This reflects both a timing issue in terms of risk ownership and an expectation that, in the short to medium term, insurance will protect assets. The main exception is in the infrastructure sector, especially in the water industry (see B2, B3, B4).
- There is currently no common method or metric for firms to assess adaptation or resilience efforts of their counterparties, a key barrier for the financial sector in particular. Current

information stems from self-reported surveys or qualitative indicators. Evidence shows a disconnect between understanding and responding to current climate variability as compared to future climate change. Adaptation actions such as business continuity efforts, buying insurance and switching suppliers are immediate steps in response to current risks, but may not be sufficient for future risk levels. While current resilience is important, it can also create a false sense of security and act as a disincentive for considering future risks. In particular, reliance on insurance with respect to current risks can generate a false sense of security and lack of financial incentives, which leads businesses to not take adaptive action in the short to medium term. In addition, insurance is projected to become a larger cost to businesses as extremes increase, which is currently not being factored into a majority of decisions (see in particular B4).

- A key area that might support further adaptation efforts are advances in availability and accessibility of data, and digital innovations. Machine learning might be used to support decision-making by optimising climate forecasting, understanding of historical weather patterns, and supporting climate and disaster risk mapping in real time. Continued focus on this space is needed, particularly in understanding how it can be integrated with or complement existing or planned incentive schemes (B7).

#### Government and regulatory action

- Business action is influenced by a set of generic (non-sectoral) regulatory actions, including planning regulations (where to build), building codes (how to build) and environmental health and safety (EHS) standards (operations within the building, e.g., overheating in the workplace). These influence current behaviour and guidelines, and standards could be used to incorporate future risk trends. Monitoring compliance, particularly with regards to future risk considerations, is likely to be a challenge for regulators.
- There is growing government and regulatory activity on risk disclosure.
- Regulators in the finance sector have adopted climate change strategies and play an important role in increasing the evidence base by supporting stress testing, scenario analysis and disclosure.
- Further investigation of the role of regulators outside of the finance sector is required to understand how they could create the enabling environment for further adaptation and provide more strategic and systemic analysis to guide integrated and longer-term action. Currently, regulators are mainly focused on aspects such as competition and consumer protection.
- Government has not mainstreamed adaptation into its Industrial Strategy, and in particular climate risk is not a focus of the Government's guidance on best policy principles for developing a local Industrial Strategy. Moving forward, it is imperative that these strategies consider climate risk and adaptation as drivers of economic policy. However, the Green

Finance Strategy does identify climate resilience and an increase in adaptation as strategic objectives, creating an opportunity for further action on adaptation finance.

- Companies cite a lack of information, as well as a lack of support and advice from Government as key barriers to adaptation action. They request help with accessing the right information and understanding what tools and measures can help reduce physical climate risks.
- There is also a role for government in supporting businesses to take advantage of the opportunities of climate change, i.e., addressing the barriers that will allow businesses to realise potential benefits, such as new markets, from climate change (see B7).

## Action for government

<b>Table 6.1</b> Urgency scores for risks and opportunities to business and industry					
<b>Risk number</b>	<b>Risk/Opportunity</b>	<b>Urgency scores</b>			
	<b>Risk/Opportunity</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>B1</b>	Risks to businesses from flooding	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
<b>B2</b>	Risks to businesses and infrastructure from coastal change	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)	More action needed  (Medium confidence)
<b>B3</b>	Risks to businesses from water scarcity	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Low confidence)
<b>B4</b>	Risks to finance, investment and insurance including access to capital for businesses	Sustain current action  (Medium confidence)	Sustain current action  (Medium confidence)	Sustain current action  (Medium confidence)	Sustain current action  (Medium confidence)
<b>B5</b>	Risks to business from reduced employee productivity due to infrastructure disruption and higher temperatures in working environments	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Low confidence)
<b>B6</b>	Risks to business from disruption to supply chains and distribution networks	More action needed  (Low confidence)	More action needed  (Low confidence)	More action needed  (Low confidence)	More action needed  (Low confidence)
<b>B7</b>	Opportunities for business from changes in demand for goods and services	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Low confidence)	Further investigation  (Low confidence)

### How strong is the evidence base?

- The evidence base has increased since the CCRA2, which broadly reflects growing awareness particularly amongst larger corporates, driven by regulatory pressures (particularly in the financial sector) and interest from investors who are demanding greater risk disclosure.
- The Task Force on Climate-related Financial Disclosures (TCFD)'s risk framing (physical risk, transition risk and liability risk) is being adopted by a number of companies in the financial sector and other sectors. However, self-reporting and most published case studies and assessments remain qualitative.
- Physical and transition risks are usually assessed separately by businesses, given the complexity involved in modelling and quantifying each. At present, these are often 'silo-ed' with transition risks dominating current discourse while physical risks are considered as only relevant in the long-term. The possibility of the lock-in<sup>1</sup> of physical risk - through, for example, risk-insensitive site location decisions or real-estate investments - are not typically being considered in risk assessments (see in particular B1, B2, B4, B6).
- For smaller and medium sized businesses, the evidence base remains very limited. We note a discrepancy of available information between small and medium-sized enterprises (SMEs) and larger companies, and listed versus non-listed companies, creating a knowledge gap that requires urgent attention, especially given the importance of SMEs to the UK economy. This applies across all risks identified.
- Overall, the data available for this report is still too limited for a systematic assessment of risks across sectors, company sizes and regions. Data either do not exist or remain outside the public domain, privately held by companies that have undertaken their own physical climate risk and adaptation studies.
- In particular, the evidence base (including for the devolved administrations - DAs) lacks geographically specific information, making a systematic assessment at the regional level based on the literature impossible.
- Results across sectors and risks are difficult to compare as underlying methods, assumptions and assessments vary significantly.
- For businesses operating at a global scale, it is unclear how to combine or compare UK-focused climate information with other national, regional or global risk tools.

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<sup>1</sup> Lock-in is defined and expanded upon in Chapter 2

What further analysis is needed to close key knowledge gaps?

- A more systematic and comparable assessment of hazard, exposure and vulnerability to ensure comparability across risks, sectors and regions is needed. This should consider both direct and indirect impacts.
- Better visualization of geographical variations and clusters.
- Joint assessment of physical, transition and litigation risks and their interdependencies across different climate scenarios.
- Quantitative analysis of international interdependencies.
- Cross-sectoral evaluation of private sector adaptation action, including the effectiveness of action taken and the role of risk disclosure as a catalyst for more adaptation.
- Assessment of the effects of Net Zero, including the synergies or trade-offs (including potential mal adaptation) with climate risks and opportunities.
- Considering lessons learned and interdependencies from the COVID-19 pandemic.
- Appraisal of effectiveness of adaptation action and government policy in influencing or creating the enabling environment or incentives for business adaptation.



## 6.1 Introduction

### 6.1.1 Scope of the chapter

CCRA3 is concerned with physical climate risks, considering current and future impacts from extreme weather events or changing climatic conditions affecting the UK. This chapter reviews the current and future climate risks and opportunities for business and industry<sup>2</sup> in the UK. It outlines current and planned adaptation directly undertaken by companies and discusses benefits of further action. The main purpose is to inform government action to support private sector adaptation between 2023-2027.

Climate risks are determined by hazard, exposure, and vulnerability (see Chapter 2: Watkiss and Betts, 2021) for more information about the underpinning CCRA3 methodology). For risks to businesses and industry this requires an understanding of:

- changes and trends in different climatic hazards. This is provided in Chapter 1 (Slingo, 2021), which reviews the latest science on a range of hazards and summarizes how climate change and natural variability are impacting the severity and frequency of these hazards across different parts of the UK.
- factors that determine how these changes impact businesses and industry. This includes location, design and building characteristics that influence current and future exposure levels for different types of assets, employees and customers, and drivers of vulnerability including businesses' processes, behaviour, products/services, demand, relationships, business-size, adaptive capacity, regulatory framework, awareness, and governance, as well as existing adaptation.

The interplay of climate hazards with these factors is investigated in this chapter based on the 3-step CCRA3 methodology:

1. What are the risks and opportunities today and in the future? Are there thresholds, lock-ins or cross-cutting risks?
2. Are the risks being managed, taking account of government and other action? How do we know what adaptation action is happening and what is known about adaptive capacity?
3. Are there benefits from further action over the next five years, over and above what is already planned?

This methodology is applied to seven priority areas identified for CCRA3, based on a business function approach that allows investigations across sectors and business sizes (see Appendix for more details).

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<sup>2</sup> The term 'business and industry' is used to capture the whole of the private sector engaging in commercial activity in the UK, from SMEs to large multinational companies.

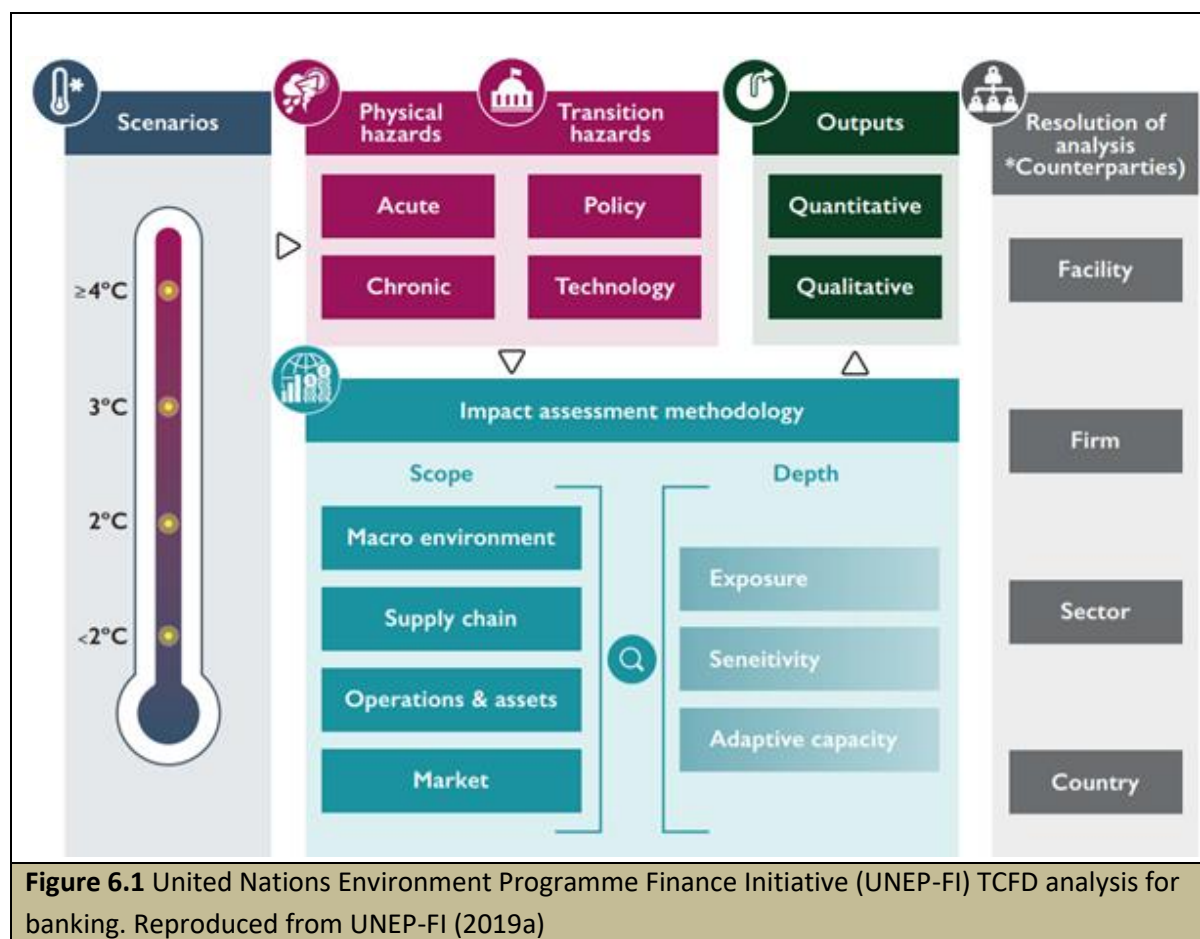
We consider both direct and indirect impacts where evidence is available. For instance, flooding can directly damage infrastructure and subsequently disrupt the supply chain. We then draw overall conclusions by reflecting on the issues across sectors, the role of firm characteristics (e.g., business size, international market connectivity and adaptive capacity) and finally provide an urgency scoring for adaptation responses. CCRA3 also focuses on lock-in and threshold effects faced by businesses. Lock-in effects involve actions or decisions today that ‘lock-in’ the potential for future climate risk and are difficult or costly to reverse or change later (see Chapter 2: Watkiss and Betts, 2021). This can occur through choices about site location, infrastructure, supply chain networks or core business models, which are difficult to reverse and can increase exposure to subsequent risks. For instance, lock-in to site location may expose businesses to future flooding risk. Threshold effects are discussed with respect to biophysical, engineering or policy thresholds, and involve levels or states beyond which there is step-change in risks, and which may necessitate much greater levels or different types of adaptation. For example, increased demand for agricultural products or tourism services, are subject to temperature thresholds and are likely to occur for a specific duration. In business functions such as access to capital, there is a significant increase in the magnitude of risk once thresholds, like limits to affordability or insurability, are reached. Barriers to adaptation, like short-termism in business adaptation planning are also discussed. This is intended to assist in identifying adaptation pathways using the CCRA3 building blocks for early action.

### 6.1.2 Risk framing in this chapter

Although CCRA3 focuses on physical climate risks, businesses are also exposed to transition risks arising from the shift to a low carbon economy, and to liability risks. These three risks were defined by the Bank of England (PRA, 2015) for insurance companies as follows:

- Physical risks are the first-order risks which arise from weather-related events, such as floods and storms. They comprise impacts directly resulting from such events, such as damage to property, and also those that may arise indirectly through subsequent events, such as disruption of global supply chains or resource scarcity.
- Transition risks are the financial risks which could arise for insurance firms from the transition to a lower-carbon economy. For insurance firms, this risk factor is mainly about the potential repricing of carbon-intensive financial assets, and the speed at which any such repricing might occur. To a lesser extent, insurers may also need to adapt to potential impacts on the liability side resulting from reductions in insurance premiums in carbon-intensive sectors.
- Liability risks are risks that could arise for insurance firms from parties who have suffered loss and damage from climate change, and then seek to recover losses from others who they believe may have been responsible. Where such claims are successful, those parties against whom the claims are made may seek to pass on some or all of the cost to insurance firms under third-party liability contracts such as professional indemnity or directors’ and officers’ insurance.

Framed by the Bank of England in their 2015 report on insurance (PRA, 2015) this has now become a common typology also applied by companies beyond the insurance sector and regulators when assessing, disclosing and reporting climate risk exposure and has led to the development of different assessment methodologies and frameworks including those recommended by the Taskforce on Climate-Related Financial Disclosure (TCFD). See Figure 6.1 for a framework developed for the banking sector.



In this chapter we reflect on information that is emerging from the TCFD process with regards to physical risks, and we also consider current limitations and the need for innovation to further the understanding of climate risks to businesses. However, we do not investigate transition or liability risks. Going forward it will be important to understand the interactions between these different risk types, particularly in the context of net-zero-ambitions or to understand how changes in physical risk trends are driven by changes to emissions and over what time frame. Similarly, it will be important to start including assessments of liability risks and related reputational implications which are expected to be influenced both by how companies manage their own risk and that of others. This includes the question of managing physical risks, although so far, most business experience in assessing climate risk has been in the context of not doing enough to reduce emissions rather than not adapting. However, in the context of creating and enhancing risk levels this is likely to stretch across transition and physical risks. Assessing and monitoring this will be important for corporates

and regulators alike. The integration of different types of risk into a risk assessment is an important consideration for the CCRA process and should be considered for CCRA4.

### 6.1.3 Terminologies

CCRA3 has an agreed glossary and key terms are set out in Chapter 2: Box 2.1 (Watkiss and Betts, 2021). For this chapter it is important to recognize that companies use a wide range of terms to describe risks, opportunities and their response to climate risks, including, but not limited to ‘business continuity’, ‘business interruption’, or ‘supply chain management’ and ‘due diligence of counterparties’. This was also highlighted in CCRA1 and CCRA2. One term widely used by firms is ‘resilience’, however definition and meaning of this can vary widely<sup>3</sup>. The IPCC (2014) defines resilience as “the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation” (IPCC, 2014). In a more specific business context, business resilience to climate change is about “preparing for the physical risks associated with climate change while at the same time shifting to a net-zero emissions future. A recent report from the World Business Council on Sustainable Development suggests that a truly resilient business also works to protect nature and achieve resilient communities” (WBCSD, 2019). Organizational resilience is also referred to in the business context. By definition, organizational resilience is “the ability of a system to withstand changes in its environment and still function. It is a capability that involves organizations either being able to endure the environmental changes without having to permanently adapt; or adapting to a new way of working that better suits the new environmental conditions.... it reaches beyond risk management towards a more holistic view of business health and success” (Johnson, 2018).

Different definitions for resilience exist across companies and sectors, as “climate resilience is important for all sectors of the economy, but it will look and feel different across industries and activities. For example, the agri-food sector and water-intensive industries are highly vulnerable to physical climate- and nature-related risks and equity of rural communities. The energy sector’s challenges are in ensuring security, equity and sustainability; the built environment is facing new demand for sustainable and functional structures that can withstand climate-related impacts” (WBCSD, 2019). Implicit in the business definition of resilience is “the requirement for flexibility and adaptability as well as the capacity to absorb market and environmental shocks” (Manning and Soon, 2016). There are also business function-specific terminologies such as: supply chain management, resource security and water and flood risk management (Agrawala *et al.*, 2011; BCI, 2018b). To this end, actions undertaken by businesses to adapt (i.e., to enhance resilience as above) may be part of their standard risk management procedures and may not be explicitly reported (Averchenkova *et al.*, 2016).

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<sup>3</sup> Chapter 2 states that ‘in CCRA3 we try and avoid the term resilience due to the lack of a commonly applied definition, unless it is used in existing Government policies, or in plans or actions as stated by the private sector or other groups, in which case the specific definition should be included.’ However, the term “resilience” is often used by the private sector instead of adaptation and we therefore include it in this chapter when the primary evidence uses the term ‘resilience’.

### 6.1.4 Interdependencies across other chapters

It is important to read this chapter in conjunction with other CCRA3 chapters as physical climate risks and their impact on businesses in the UK are highly interdependent, with a range of cross-cutting aspects that are relevant to Chapter 6 but covered elsewhere in the CCRA3 Technical Report (Betts et al., 2021), as summarized in Table 6.2 below.

<b>Table 6.2 Interdependencies between Chapter 6 and other chapters</b>	
<b>Chapter</b>	<b>Interdependencies with Chapter 6</b>
Natural environment and assets (Chapter 3)	<ul style="list-style-type: none"> <li>- Changes in the natural environment impact natural capital, particularly in agriculture and fisheries as business sectors</li> <li>- Eco-system services can help manage risk – loss of nature-based solutions can lead to increased exposure of businesses to physical risk (e.g., loss of natural flood management for business sites)</li> <li>- Interdependencies with natural infrastructure, flood risk management services provided and blue-green infrastructure particularly in the context of coastal areas and marine environment</li> <li>- There are ecosystem-based adaptation opportunities for businesses, but experience and trust are low.</li> <li>- Climatic impacts on the natural environment can have implications for corporate net-zero strategies (reforestation, carbon sinks)</li> </ul>
Infrastructure (Chapter 4)	<ul style="list-style-type: none"> <li>- Most business functions depend on reliable infrastructure, with disruptions a key risk for site operations, access to markets, supply chain and distribution networks, employee productivity</li> <li>- Businesses most concerned about disruption of energy, ICT infrastructure, transport and water supply</li> </ul>
Health, communities and the built environment (Chapter 5)	<ul style="list-style-type: none"> <li>- Overheating of buildings poses risk to employee productivity</li> <li>- Health and staff well-being are a concern for businesses.</li> <li>- Business responses to climate risks can lead to inequalities – for example low access to capital and insurance for exposed households (e.g. due to risks faced by banking and insurance sectors)</li> <li>- State of built environment and adaptation responses depend on business action, including investment and construction procedures</li> </ul>
International dimensions (Chapter 7)	<ul style="list-style-type: none"> <li>- Imported risks through business value chains are likely to have bigger implications than domestic risks for those businesses involved in trade, relying on global supply chain or distribution networks</li> <li>- Risks to agri-businesses from changes in global food production</li> <li>- Global exposure of UK financial sector through international nature of transactions</li> <li>- Also offers opportunities for new services and solutions</li> </ul>

### 6.1.5 Evidence base

Over 366 sources of academic peer-reviewed literature and ‘grey literature’ were consulted for this chapter. As in CCRA2 peer-reviewed academic evidence is still limited for the business sector and accounts for 29% of the overall literature. Moreover, around 76% of the grey-literature comes from the private sector or third parties. For example, consultancies and consortiums conduct their own surveys, for example the annual Business Continuity Institute (BCI) Supply Chain Resilience Index (BCI, 2019a). Increased consideration of climate risk by businesses is illustrated by a rise in advisory reports from accountants, banks and insurers, and more discussion in overarching risk reports such as the Global Risk Report 2019 (World Economic Forum, 2019). Literature in certain industries such as finance and professional services has significantly increased following the TCFD, however the scope is often global rather than country specific (Deloitte, 2018; PwC, 2017; UNEP-FI, 2018; ICAEW and Carbon Trust, 2018). Importantly the accessibility of such grey literature is often difficult where business, consultancies or their advisors may not be able to share client reports.

The evidence base has expanded from CCRA2, partly due to initiatives such as the TCFD, which has increased voluntary business self-disclosure (UNPRI, 2019). In the UK, the Government endorsed the recommendations of TCFD and encouraged all listed companies to implement them. 1,440 organizations have pledged support to TCFD, including eight of the ten largest asset managers and twenty of the largest banks. Many companies in the UK have also committed to implementing the TCFD recommendations, and this increase in climate-related financial disclosures helps to build the evidence base in this area, particularly from the financial sector. Implementing TCFD recommendations will become mandatory from 2023.

The LSE Climate Risk Business Survey 2020 (Mathews and Surminski, 2020) was undertaken specifically for CCRA3 and aims to address current literature gaps. The LSE Business survey ran from 21st November 2019 – 2nd March 2020 and was open to businesses across the UK. The survey was shared with business stakeholders (e.g., business associations, consultancies etc.) participating in the CCRA3 process and circulated with their business contacts and through the author’s network. Business participation was voluntary, and all results were anonymised. Businesses reported their current and future climate risk/opportunities, financial impact and adaptation strategies. They also reported on their climate risk preparedness, reporting, and engagement with internal and external stakeholders. The survey received 225 responses from across the UK and a wide range of sectors (e.g., Agriculture, Manufacturing and Services). Most respondents were small businesses with 0-4 employees and the majority had turnover of £50,000+. The survey contributes to the nascent firm-level evidence in the UK, particularly concerning climate risk perception of SMEs. However, survey results should be treated as indicative as the sample size was limited and non-representative across sectors and countries. Moreover, to increase participation, the survey was open to respondents with different roles in the business (e.g., CEO, CRO), which may have influenced the subjectivity of some responses.

In addition, we also considered business disclosure under the CDP Climate Change Disclosure 2018 survey, which includes responses from 176 companies operating in the UK (CDP, 2018). The survey includes self-reported information about physical risks, resilience opportunities, financial impact and costs of management. Businesses also self-report on time horizon, likelihood, and magnitude of

risks, which were used to inform urgency scoring. Comments on adaptation strategies considered/and or adopted were also analysed. Further information can be found in the Appendix.

We conducted consultations and engagements with the devolved administrations to account for regional evidence. There are some local/regional examples of assessments, such as for the City of Glasgow, that provide information about risk and adaptation levels. This information has been incorporated wherever possible.

Literature review and surveys were also complemented with stakeholder engagement activities, which included: Climate Change Committee (CCC) led stakeholder events, a business roundtable event as part of LCCP/London Climate Week (July 2019), business association roundtable discussions (including Aldersgate Group, ABI, UK Green Building Council, Zurich Insurance, Willis Towers Watson) and individual business discussions. These events provided a bottom-up perspective to supplement the literature surveyed. As part of the evidence collection and stakeholder engagement we also compiled a set of case studies and text boxes to illustrate risks, opportunities and adaptation efforts. A full break-down of the evidence (as of 31st August 2020) is below (Table 6.3). This is more exhaustive when compared to CCRA2, which relied more heavily on business input from larger companies. For example, the gap of focusing on FTSE 100 companies (e.g., CDP data) was addressed using the LSE Climate Risks Business survey from 2020 which predominantly focused on smaller UK businesses. Survey results are illustrative but come with significant health warnings and can't be considered representative due to comparatively low response rates (when considered in the context of the overall number of businesses in the UK). Engagement with trade associations and representative bodies such as CBI should be strengthened further for CCRA4 to ensure wider reach. In addition, most surveys are based on board level perception of climate risk, which may vary from action on the ground. Moreover, self-reporting is influenced by terminologies, timescales and climate models adopted. Thus, information remains fragmented and sector specific, preventing comparisons from being made.

Similar to CCRA2, most of the literature in the evidence base is qualitative. Out of the 366 sources reviewed, only 132 (36%) were quantitative in nature. Table 6.3 provides an overview of the types of evidence consulted.

Despite the increase in evidence from CCRA2 to CCRA3 there are significant limitations:

- There are no clear indicators that show whether vulnerability and exposure to extreme weather is increasing or decreasing, in England and Scotland at least (CCC 2019a).
- Quantitative evidence of the magnitude of impacts is not available on a systematic basis across risks, type of companies, sectors or regions including DAs.
- While the number of assessments is increasing, the variety of climate models, scenarios and projections used makes comparison difficult.
- The evidence is not sufficient in volume and detail to comprehensively test the National Adaptation Programme (NAP)<sup>2</sup> vision of business resilience (CCC, 2019a), and similar statements provided in the adaptation programmes of the devolved administrations.
- Commercial sensitivity makes business information hard to obtain and verify.

**Table 6.3** Summary table of all the evidence consulted

Type of evidence	Numbers of sources for CCRA3
Academic literature	105
Grey literature	261
Business surveys	15
Reports	44 (Government) 106 (Other)
Guides	17 (Government) 12 (Other)
Tools	12
Online sources (Article, blog, news, press release, podcast, letter etc.)	53
Dataset	2 (ONS, 2018;2016)
<b>Total</b>	<b>366</b>

### 6.1.6 Socio-economic scenarios

Social and economic trends are highly relevant to the future risks of climate change, and strongly influence future magnitude through changes in exposure and vulnerability (Chapter 2: Watkiss and Betts) as well as adaptation, in terms of the capacity to act. Climate and socio-economic factors can act together as risk multipliers, although for some cases, socio-economic change can reduce vulnerability and thus dampen impacts. The evidence that underpins this chapter does not follow a consistent approach for socio-economic projections: some studies do not include any socio-economic factors, others set out a range of different assumptions which makes comparison difficult. This will require further attention when planning for CCRA4. To achieve a more consistent approach for specific CCRA-related research projects the CCC commissioned a new consistent set of UK socioeconomic projections from Cambridge Econometrics (CE) (CE, 2019). These include projections of population growth, population ageing, and migration (internal and immigration), presented in Chapter 5 (Kovats and Brisley, 2021). The central scenario assumes that the UK population grows at a steady pace, increasing by over 17 million (compared to 2016), to reach a total population of almost 83 million in 2100 (CE, 2019). The central population projection is based on the ONS 'principal projection scenario', which assumes demographic patterns in future such as fertility, mortality and migration trends remain the same as current trends (CE, 2019). Of particular relevance to this chapter, the scenarios also include projections of economic growth. The CE (2019) projections provide central, low and high estimates for total GDP (£ millions, real) and % growth (from the previous year) based on estimates from the Office for Budget Responsibility (OBR). The Central scenario envisages a GDP annual growth rate for the UK of about 1.6% from 2018 to 2028 and an acceleration with GDP expected to grow by 2.2% per annum from 2029 onwards (through to 2100). The figures used for the CE 2019 analysis will require updating in light of the COVID -19 pandemic and the impact on growth.

The increase in economic growth has a major influence on the magnitude of future risk for businesses. There is projected to be a large increase in the value at risk, in terms of assets which



increases the potential exposure to risk, though future economic growth could provide additional resources to address these risks.

It is stressed that the CCRA research project on flooding, which is the most important risk identified in the chapter, does not take this economic growth into account and only considers population growth. The CE analysis also projected gross value added (GVA), employment and labour productivity, all of which are important for the business sector. The GVA projections were based on current value, and future GDP and population, and include values by sector. Labour productivity (derived from employment and GVA) is projected to grow across all sectors

There are also relevant global socio-economic drivers and projections thereof. This adds another dimension of complexity to the consideration of international business risks because it is not just the changes in global physical climate risk that affect the UK, but also the changes in socio-economic trends and the multiplication or dampening of international risk. There are global socio-economic projections available in the IPCC Shared Socio-economic Pathways (SSPs), outlined in Chapter 2 (Watkins and Betts, 2021), which include data at the country level internationally for five alternative pathways. However, CCRA3 does not work with the SSP framing, and it would be extremely difficult to use these in a synthesis exercise such as CCRA3. This is discussed further in Chapter 7 (Challinor and Benton, 2021) in the context of international risks.

### 6.1.7 Net Zero

During the period that the CCRA3 was undertaken, UK and Scottish Net Zero targets were legislated.<sup>4</sup> There is not yet a Government analysis of how this target will be achieved, but it could have a major influence on businesses, and the climate risks and opportunities they face. To investigate this, CCRA3 added two questions to consider;

- i) If the Net Zero target is likely to increase or decrease the CCRA3 risk/opportunity and
- ii) If the climate change risk or opportunity could make the Net Zero target easier or harder to achieve? Given the current state of evidence (on Net Zero), these questions were addressed qualitatively throughout CCRA3. The Net Zero target will have important implications for all businesses in the UK and their domestic operations and footprint and will also influence future investment strategies through transition risks (see above). The interplay between physical climate risks and the shift towards a Net Zero carbon economy remains under-investigated. It is clear that in the long-term a successful shift to Net Zero will help limit physical impacts, however there could be trade-offs at least in the short term, where responding to extreme events such as flooding and heat waves could entail energy and resource intensive processes that may also affect the ability of companies to achieve their carbon emission reduction targets.

Overall CCRA3 shows that there is a discrepancy in business awareness and also a lack of joined-up assessments of risk and opportunities arising from physical climate change and transition to Net

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<sup>4</sup> The Welsh Government have committed to legislating a 95% target with an ambition to set a Net Zero target. The Northern Irish Government has also requested the advice of the CCC on an equitable contribution to the UK's target (CCC, 2020a).

Zero. For instance, businesses are predominantly responding to climate risks via Net Zero targets and climate mitigation strategies. This is in line with transition risk response (under the TCFD framework) or industry-wide commitments. For instance, in CDP's Climate Change Disclosure 2018 survey (CDP, 2018), many businesses listed responses such as emissions reduction as part of their strategies to manage physical climate risk. This conflation of preparedness for climate hazards with emissions reductions means physical risks remain neglected in business strategy and underreported. Importantly business decisions taken today will impact both the ability to transition to net zero and the ability to cope with physical risks.

### 6.1.8 Hazard-specific observations

Chapter 1 (Slingo, 2021) provides an update on the latest scientific understanding of climate hazards based on UKCP18. This offers the first point of information for assessing climate risks for business and industry, summarizing the UK hazard component of the risk equation. There is also a set of hazard-specific observations that indicates where hazards might have broader implications on businesses than through the risks identified in this chapter.

- Flooding is the costliest hazard. In this chapter we consider general flood risk (risk B1) and then assess specific coastal risk (risk B2). Across the different types of flooding, surface water, groundwater and drainage-related risks tend to be less understood by businesses than flooding from rivers or the sea. For CCRA4 we recommend a specific focus on surface water flooding due to the applicability across the country and the impact on areas that have traditionally not deemed to be at flood risk.
- Windstorm risks have been assessed in terms of direct damages and the impact on insurance (risk B4). However, extreme windstorm events can cause significant disruption and cause indirect losses, for example from failure of infrastructure or supply chains.
- Heat impacts on businesses in the UK are recognized in the chapter in the context of labour productivity (risk B5) but there is growing evidence of wider opportunities and risks: high temperatures can also cause irregularities for the cycle of agriculture such as fruit farms, which can damage the quality of the crops or lead to lower yields. For instance, heatwaves and extreme temperatures affect livestock productivity, which significantly impacts agriculture businesses. In Scottish agriculture (Ecosulis, 2019), the biggest impact of extreme weather was in the sheep sector with losses of £45 million during 2017/18. Such business level losses need further investigation in CCRA4. Similarly, the UK Centre for Ecology & Hydrology (UKCEH, 2020) found that increased temperature thresholds impact wheat yields, milk production, parasite outbreaks in livestock and contribute to drought and soil erosion which all affect agricultural business productivity (see also Chapter 3: Berry and Brown, 2021). For instance, for milk production, at the UK level, the estimated economic impact currently ranges from £3 million to £4.5 million per annum. Costs increase to between £8 million to £13 million by the 2050s, and to between £17 million to £57 million in the 2080s. Heat impacts are also likely to have manufacturing and process industry efficiency and quality impacts. For CCRA4 we recommend investigating heat impacts in greater detail, including the impact on building materials and production processes, as well as analysing potential implications for achieving Net Zero.

- Subsidence caused by drying clay soils may increase with hotter, drier summers, and can affect the structural integrity of buildings and underground telecommunications cables and can damage assets and commercial buildings. We notice a lack of specific assessments despite the experience with subsidence in several parts of the UK due to soil composition (Chapter 5: Kovats and Brisley, 2021). For CCRA4 we recommend an assessment of the interplay of subsidence risks with other risk drivers. Long-term hotter and drier temperatures can lead to infrastructure and building damage or the overheating of buildings.

### 6.1.9 Spatial aspects

Across the UK, current hazards vary geographically and are projected to change differently by location with future climate risks, with regional and local hot-spots emerging for example along the coast or in drought-prone areas. For this chapter, this implies that the exposure of businesses and their different functions depends on locations and geographies. This can be direct – locations of sites for example, or indirect – impacts on transportation, markets and demand. A visualization of this across different hazards through maps is still missing. While far from exact, it would allow an initial regional assessment to see which hazards are expected to be of concern. Currently hazard maps are available, and these can be supplemented with information about location of business sites, water usage, number of employees in offices, agricultural activities and flow of supply chains and distribution networks to gain a better overview of spatial distributions of risks. Importantly, asset-level information is often not available or not in the public domain. For this chapter we capture evidence across different scales from local to national, while international aspects are captured in Chapter 7 (Challinor and Benton, 2021).

A challenge for many businesses is the variety of tools and instruments and their different spatial scope. Some recent initiatives and assessments such as TCFD imply a global perspective and reliance on international models as well as the UK's own climate models. New computing capacity and improved access to data can help address the challenges, however, the utilization of any risk data in day-to-day business processes remains difficult for many companies, particularly smaller-sized companies. Furthermore, one problem for many practitioners in the business and industry communities is that climate data can be too complicated, preventing them from using or integrating it into their own business models and tools. Importantly, new data and computational power can only help in building adaptive capacity if deemed usable and relevant by businesses. Our stakeholder engagement reveals that the lack of sector-specific scenarios and region-specific risk assessments pose an information gap for companies. For example, engagement with insurance brokers and catastrophe modellers reveals that there are significant gaps in knowledge and understanding about current and future risks, particularly when considering the interplay between hazards and vulnerabilities. The confidence in industry assessments of climate change impacts remains low despite the wealth of expertise in general risk analytics. Furthermore, companies that are attempting to assess climate impacts are confronted with a very wide range of tools and approaches. Initially considering different warming scenarios up to 3°C, companies more recently have started including 4°C scenarios in these assessments. One example is the methodology applied by Mercer (2019) in their sequel to the 2015 flagship report on investment risk from climate change,

classifying physical implications of different warming scenarios as follows +2°C=meaningful physical damages; +3°C=highly disruptive physical damages; +4°C=severe physical damages (Mercer, 2019).

#### 6.1.10 Business engagement

Business engagement in CCRA-related discussions has increased since CCRA2, which appears to be in line with growing climate awareness, recent public discourse and regulatory change in the finance sector. Business discussions also reveal significant concern about possible reputational issues arising from inaction or failure to withstand climate risks. Overall business involvement in climate risk assessments is fairly limited (Howarth *et al.*, 2017) and tools and methods developed in the private sector tend to be disconnected from those used by the public sector, including for CCRA purposes. This requires further discussion for CCRA4 to see how the growing knowledge in the private sector including commercially sensitive information about risks and risk trends could be better utilized. The current push for increased transparency and climate risk disclosure is expected to lead to better understanding of risks for listed companies and should provide more insights into corporate exposures. For CCRA3 we have explored this through stakeholder workshops and discussions with trade bodies and individual companies. Of particular interest is the engagement of those companies who themselves conduct risk assessments and own tools that could be of use for CCRA.

Business engagement is also occurring at the trade association level. There are examples in sectors like real estate (Royal Institution of Chartered Surveyors - RICS), industry (Confederation of British Industry - CBI), insurance (Association of British Insurers - ABI), accountancy (Institute of Chartered Accountants in England and Wales - ICAEW) and agriculture (National Farmers' Union of England and Wales - NFU).

One of the biggest challenges of a country-wide risk assessment is the balance between aggregated national level information and sectoral specificity. CCRA2 and CCRA3 do not investigate risks according to business sectors in an effort to avoid sectoral silos. However, for companies, the main interest is likely to be in issues relating to their peers, customers and suppliers, hence a better understanding of risks by sector might be needed. This will require further investigation for CCRA4.

#### 6.1.11 Importance of focus on small and medium-sized enterprises (SMEs)

CCRA1 and CCRA2 have highlighted the low adaptive capacity across SMEs. The CCRA3 analysis confirms this and identifies particular challenges for smaller companies across most sectors and risks. Across regions and risks there is a key urgency in supporting SMEs. SMEs appear less proactive than larger corporates in terms of addressing risks, due to a narrower range of skills available to them, limited information and low levels of understanding of operational risk posed by climate hazards.

The evidence base is often much weaker compared to larger corporates as there are fewer studies on SMEs and less information is being reported or disclosed by those companies. Power *et al.* (2020) study on behavioural changes as part of CCRA3 also notes that the adaptation decision-making processes of SMEs seem more similar to that of individuals, as opposed to large corporations which tend to be driven by corporate governance processes and shareholder reporting. Overall SMEs seem

less likely to have business continuity plans in place than larger businesses, and the evidence points to deficits in adaptation action by SMEs and lack of government support aimed at SMEs.

Key observations related to SMEs:

- In relation to risk B1, there is little evidence of planning or implementation of flood adaptation being done by SMEs. In Power *et al.* (2020)'s study on behavioural changes, less than 20% of SMEs surveyed had taken any permanent protective measures against flooding.
- Regarding risk B3, there is evidence that businesses are investing in ecosystem services, but it would be useful to have a national survey of SMEs to see how widespread these actions are.
- For risk B4, access to capital and insurance is expected to pose a greater problem for SMEs.
- In 2020 the Welsh Government surveyed 243 SMEs regarding risk B5, higher working temperatures and infrastructure disruption, and found that most businesses don't see climate risk as a pressing issue, are unclear on the risks, and few are taking action.
- In addition, although there are increasing climate advisory, consulting and accounting services (risk B7), SMEs lack the resources to utilise these services. At the same time there are significant opportunities for innovation and entrepreneurial activities that SMEs can drive in response to climate risks, but as highlighted in risk B7, there are many barriers that appear to prevent SMEs from gaining advantages from anticipating changing markets. This includes as upfront cost barriers to entering new markets and inertia of the industry.
- Adaptation requires agility and the ability to react to gradual and sudden changes. There are some examples of SMEs realizing opportunities in the face of adversity – for example instance in Section 6.3, the SME community-level engagement example of a furniture store being rebuilt on stilts in Mytholmroyd to strengthen its flood resilience is an example of a business success story that could be mirrored elsewhere.

There is therefore urgency across all parts of the UK to support SMEs in accessing information, funds and skills to address the climate resilience challenge.

### 6.1.12 Natural Capital

There are many direct links between business and industry and natural capital (the elements of nature that directly or indirectly produce value for people) including ecosystems, species, freshwater, land, minerals, the atmosphere and oceans, as well as natural processes and functions. Dependency on natural capital can impact several business functions and create risks to supply chains, resources, liabilities, customer base and reputation. Overall, for adaptation and climate resilience there are two features particularly relevant for this chapter:

- how do climate impacts on natural capital translate into business risks?

- how is the natural environment mitigating climate risks for businesses through ecosystem services and are businesses actively supporting this risk mitigation function through investment?

The impact of climate change on natural capital is outlined in Chapter 3 (Berry and Brown, 2021) and by the CCRA3 threshold research project. This creates risks for businesses, as most prominently seen in the agricultural, forestry and food sector who are directly linked to natural capital, but other sectors are also at risk, particularly due to supply chain risk (national and international) or in relation to water availability and quality. The TCFD (WBCSD, 2020) maps the repercussions of hazards (e.g. droughts and heat stress, flooding and water scarcity) on ecosystem services (e.g. crop productivity) causing business impacts (e.g. sales, operations and supply chain) and financial impacts (increased Capex, procurement costs and lost revenues). This means businesses reliant on natural assets are particularly vulnerable to climate risk.

However, despite the intrinsic connections between natural capital and agricultural businesses, most agribusinesses view climate change impacts as a low priority compared to aspects like soil health, pest control and economic sustainability (RSA, 2019). This highlights the need to link long-term climate risk exposure with natural capital degradation. As mentioned in Section 6.21 and expanded further in Chapter 3 (Berry and Brown, 2021), the UK Centre for Ecology & Hydrology (UKCEH, 2020) is working on this link and highlights that increased temperature thresholds impact wheat yields, milk production, and parasite outbreaks in livestock - which all affect agricultural business productivity. Impact on natural capital can also be positive, such as short-term increases in crop productivity which can lead to opportunities in the agricultural, food and forestry sector. However, threshold effects may mean land-use and land-use change in some cases will detrimentally affect long-term business profitability.

Even though every business depends on natural goods and services, only very few assess or account for the value of their usage (Natural Capital Committee 2018 and 2020), and the plethora of different approaches reduces transparency and give rise to concerns over greenwashing. The Natural Capital Committee has recently recommended the use of a corporate accounting template to report business use of natural capital and corporate accounting standards as a formal audit requirement (NCC 2020). This would also have implications for the understanding of physical climate risks: companies need to know what natural capital they are consuming as that will help them begin to understand how they are vulnerable to climate impacts which threaten that natural capital.

In addition, businesses also do not have the necessary government guidelines or incentives for utilizing natural capital investments for climate adaptation, such as provision of environmental schemes, land-use planning or diversification. For instance, there is limited progress on adaptation initiatives under the Environmental Land Management Scheme (ELMS) trials (RSA, 2019) and investment in natural capital to support adaptation is still an emergent area for the finance sector, with the pace of translating natural capital's potential into policy and business models remaining slow (Surminski and Szoenyi, 2019). For example, ocean climate change solutions are often hindered by fragmented governance arrangements and integrating the ocean into the global financial architecture is long overdue (Berglof and Thiele, 2019). This is in part due to the disconnect between the members of society who are responsible for, and thus bearing the cost of, land management, and society at large that benefits from land management. This disconnect can lead to

sub-optimal investments in restoration and sustainable land management. Furthermore, short-term financial gains are often favoured over judicious land management practices, leading to the over-exploitation of natural resources (Blignaut, 2019).

A narrow view of climate risk has meant low uptake of solutions based on eco-system services by businesses as documented by the CDP results (Goldstein *et al.*, 2019), although this is not surprising as many benefits are non-market and thus there is a difference between the private and public perspectives of these benefits. This is in line with the LSE Survey results (Mathews and Surminski, 2020), which found that 'hard' engineering and employee-oriented solutions were more frequently adopted by businesses as compared to ecosystem-based approaches. The potential for these adaptation approaches needs to be further explored, alongside their commercial viability.

For instance, the NFU has outlined some strategies such as investment in farm reservoirs and funding for business weather forecasting capabilities which required further government support (NFU, 2018). Solutions are wide ranging from further precision in agriculture technology (Farming UK, 2019), development of regional seedbanks, supporting wild plant and animal diversity (Landworkers' Alliance, 2019) and innovative irrigation techniques (Schroders, 2018). In addition, natural flood management (NFM) (using the natural features of the land to store and slow down the flow of water) is being piloted across the UK and could be a low-cost flood risk management option for smaller communities (Wentworth and Ermgassen, 2020). A 2019 study that interviewed land managers and practitioners of flood risk management in the UK highlighted that barriers to the uptake and implementation of NFM include economic constraints for land managers, the current lack of scientific evidence to support NFM and current lack of governance over long-term responsibility for NFM, which hinders future monitoring and maintenance (Wells *et al.*, 2019). Making this work at a commercial level, under commercial financing terms, is still a key challenge for these ecosystem service focused investments.

Enhanced business awareness may increase uptake, since ecosystem-based measures, like area-based payments, often have private co-benefits (e.g., improved soil health, pollinator habitats and water quality) which farmers prioritise (RSA, 2019).

Natural capital plays a key role in achieving net zero ambitions and businesses are relying on carbon offsetting as part of their Net Zero strategies. Offsetting commitments can positively contribute to natural capital and promote ecosystem-based adaptation solutions, although most focus to date has been on energy efficiency and fuel switching. Whilst large UK aviation and energy businesses are increasingly partaking in such schemes (Financial Times, 2019), these initiatives often occur outside of the UK. Moreover, the larger benefits and additionality of these schemes have been contested in the literature (SEI, 2015). However, as we move towards Net Zero offsetting approaches that sequester CO<sub>2</sub>, (which tend to be nature based) will become more important as activities that simply reduce CO<sub>2</sub> emissions i.e., fuel switching must happen anyway.

### 6.1.13 COVID-19 implications

The COVID-19 pandemic has implications across all sectors and business types and impacts government policy as well as the adaptive capacity of companies. As the pandemic is still ongoing,

evidence of these implications is limited and still emerging, and at this point the evidence is largely anecdotal, as demonstrated below. Business engagement in the CCRA3 process has been hampered due to COVID-19, with several of the collaborations with trade bodies and associations cut short, postponed or moved to a different format during the writing stage of CCRA3. There is also anecdotal evidence that COVID-19 restrictions could hamper the speed of implementing some corporate responses, both in context of adaptation and mitigation for climate change, as engineering solutions in particular can't be executed "from home" but require significant work force located at the site (stakeholder discussions).

Overall, the pandemic appears to have increased awareness of how vulnerable societies and economies can be in the face of global phenomena, and how without foresight and planning we are left ill-prepared. (Howarth *et al.*, 2020). As such, the pandemic has strengthened the case for an economic recovery that puts emissions reduction, and indeed climate resilience, at its heart. At the same time there are growing concerns about a diversion of resources to deal with the COVID-19 crisis response and the aftermath. Amidst general concerns about diversion of resources to the pandemic response the implications for publicly funded adaptation action are as of today unclear but reduced budgets at national and local levels and reallocation of staff to respond to the pandemic could have implications for adaptation efforts.

The pandemic is also highlighting the need for a broader and more holistic approach to risk management and resilience, with growing calls for more efforts in recognizing and addressing compound and systemic risks beyond just the public health impacts of COVID-19. The Coronavirus crisis has shone a light on supply chain resilience (Financial Times, 2020a; WEF, 2020). Anecdotally and in line with previous shocks, in the current state the food supply system seems to have held up well, but the continued impact of the pandemic remains unknown. In addition, the COVID-19 pandemic has highlighted the vulnerability of extended global supply chains, built on lean manufacturing principles in general, and added to the uncertainty created by EU exit and the 2008 financial crisis. For instance, as per a recent survey by the Food, Farming and Countryside Commission (FFCC), during the COVID-19 lockdown (FFCC, 2020), farmers demonstrated less confidence in the future of food, farming and the countryside compared to other respondents. Impacts on manufacturing industries and engineering industries due to the breakdown of the global supply chain appear more significant to the UK than food supply. Stakeholder discussions revealed that even after 12 months of pandemic-related disruption there are still supply chain issues affecting the white goods market due to key component manufacture that is centralised in Asia that has still not yet returned to full production or has been reassigned to higher profit COVID-19 response products.

In general, the inability for supply chains to respond to shocks and changes in demand has been noted in the COVID-19 crisis response (WEF, 2020), and the exposure of a number of vulnerabilities in the UK food system brought on by the pandemic provides the opportunity to study how food supply chains function in crisis conditions. Rather than return to business as usual following the pandemic, companies may seek to decrease the length of supply chains while updating processes to be smarter and more agile and therefore more resilient to future shocks. All of this is likely to provide greater resilience to future climate related pressures. This is asserted by the findings of FFCC (2020), which found that 91% of respondents expressed a need for diverse and local sources of food



production. The need for shorter and diverse food supply chains with more local suppliers was also asserted. In addition, HSBC (2020) found there is some evidence that companies with long-term, sustainability strategies are weathering the consequences of current COVID-19-related supply-chain disruptions better than those who do not have such strategies in place. However, while the short-term shock of COVID-19 requires a rapid and agile response, the much longer-term impacts of climate change call for major strategic responses to supply chain disruption.

Regarding COVID-19's effect on risks to finance, investment and insurance (Risk B4), the pandemic highlights a gap in expectations of customers and insurers, which as stakeholders highlight, must be avoided in the case of climate change. There is also the difficulty in distinguishing between business interruption and contingent business interruption. Thus, contingent business interruption calls for more emphasis on business interdependencies. These business interruption risks are just as important as costs of insurance increasing or becoming available. Whilst the impacts of climate change are much more unevenly distributed than COVID-19 risks and policy response significantly different, the 2019 England CCC progress report highlighted that many businesses do not have continuity plans in place for extreme weather, possibly solely relying on insurance. Another implication of the pandemic is that climate stress-testing to encourage more scenario-based financial analysis is intermittently paused due to COVID-19 (IMF, 2020), with the Bank of England announcing the launch of its CBES exercise for June 2021 (Bank of England, 2020).

COVID-19 has spurred opportunities such as new ways of working, with remote and flexible options to maintain employee productivity during the pandemic (ILO, 2019, Day *et al.*, 2018). These behavioural changes have been tested and employed by various businesses from the onset of the pandemic, but it is unclear if the shift to remote working due to COVID-19 will be a long-term trend (Creative Carbon Scotland, 2018).

Current studies on the impact of working from home on overall productivity could offer interesting findings for coping strategies in the face of climate risks. Similarly, there are likely to be relevant lessons learned from the health and social care sectors regarding vulnerability of staff and their ability to perform their duties during the pandemic. However, the COVID-19 interventions have come at a significant cost to the economy and to welfare, suggesting that “climate change requires a more carefully planned and calibrated, inclusive, less disruptive and more sustained response” (Howarth *et al.*, 2020). There could be an opportunity if COVID-19-responses and economic stimulus would be used to strengthen resilience and support adaptation. This concept of ‘building back better’ and a green and resilient recovery are gaining traction with new research showing the broad benefits that such an approach to recovery could have, including for businesses and innovation (Vivid Economics, 2020).

Changes in demand for goods and services must be viewed in tandem with sectoral change, technological advances and the institutional and labour-market changes. Opportunities also depend on the macroeconomy. For instance, recession, employment loss and health risks post-COVID-19 limit opportunity realisation. This is especially true for the climate advisory sector, as demand for services may fall in cash-strapped sectors and amongst SMEs unless further support is provided. In Scotland, COVID-19 has had a significant adverse impact on heritage businesses (Historic Environment Scotland, 2019). This is likely to affect funds available for adaptation in the future,

exacerbating the resilience deficit. In addition, many businesses operate out of heritage assets such as traditional buildings and/or rely on heritage-driven tourism. Opportunities for business from changes in demand for goods and services (Risk B7) in the heritage sector may have longer implications due to the pandemic. At present, some bodies like the COVID-19 Historic Environment Resilience Forum (CHERF) are facilitating rebuilding, recovery and resilience opportunities. Impacts are significant given the decline in tourism post-COVID-19.

#### 6.1.14 Inequalities

The evidence consulted for this chapter suggests that SMEs have low business awareness of risk and capacity to respond to it. Most businesses that assess physical risk and quantify financial impact use in-house expertise and consultants. However, SMEs tend to have limited capacity and resources to do this. SMEs may also be more vulnerable to climate hazards due to centralised operations, limited financial capital and low investment in resilience measures such as insurance uptake. To this end, stakeholder discussions in the insurance industry have suggested extending schemes such as Flood Re to small businesses. These vulnerabilities mean SMEs are likely to exit the market when faced with frequent climate disasters. Whilst there is some evidence that SMEs (NDF, 2020), are more resilient and likely to adopt adaptation solutions, this requires further investigation.

Employment productivity disruptions from heatwaves (Risk B5) are most likely to affect low-skilled and low-waged workers in industries like agriculture or tourism as well as those working in the construction and manufacturing industries (ILO, 2019). Exposure to heatwaves also puts employees already in ill-health at greater risk. Infrastructure disruptions (Risk B2 and B5) are also likely to affect employees who often live furthest away from their workplaces, such as in the services sector. Business level repercussions such as water scarcity (Risk B3) or food security risks (Risk B6) also disproportionately affect the poor.

Physical risks are going to create sector and location-based winners and losers. Whilst there are some opportunities from climate risks (Risk B7), these are concentrated in sectors such as tourism or agriculture. Moreover, evidence is mixed. Whilst the tourism sector is expected to face greater demand from warmer temperatures, research projects suggest that many hotel businesses will face high flood risk exposure (Surminski, *et al.*, 2020; Roezer and Surminski, 2020). The manufacturing sector is expected to face high losses due to supply chain risks (Risk B6) and location-specific risks, with relocation being a less viable option (Risk B1 and B2). Wealthier businesses have more agency and capacity to take adaptative actions generally. As a specific example, for Risk B2, the Department for Environment, Food and Rural Affairs (Defra) (2018) find that wealthier businesses have more agency and capacity to take adaptative actions against coastal erosion, by for example, attempting to secure planning permission or enforce private defences. Regional discrepancies are seen in the agricultural sector, with productivity expected to increase in the North and West and declining in the East and South East (Ritchie *et al.*, 2019).

## 6.2 Risks to business sites from flooding (B1)

Current and future risks to business sites from flooding are significant, with high magnitude impacts across the UK. Costs for businesses arise from damage to sites as well as from business interruption and indirect losses such as lost production time and associated costs impacting the profitability of firms. Adaptive action such as enhanced flood protection, planning and preparedness through business continuity management is encouraging but given the scale and the wider implications for the economy and society at large, more action is needed. Thresholds including availability of insurance and costs of capital could increase magnitude even further unless risk levels are reduced through corporate, as well as community-level, adaptation action.

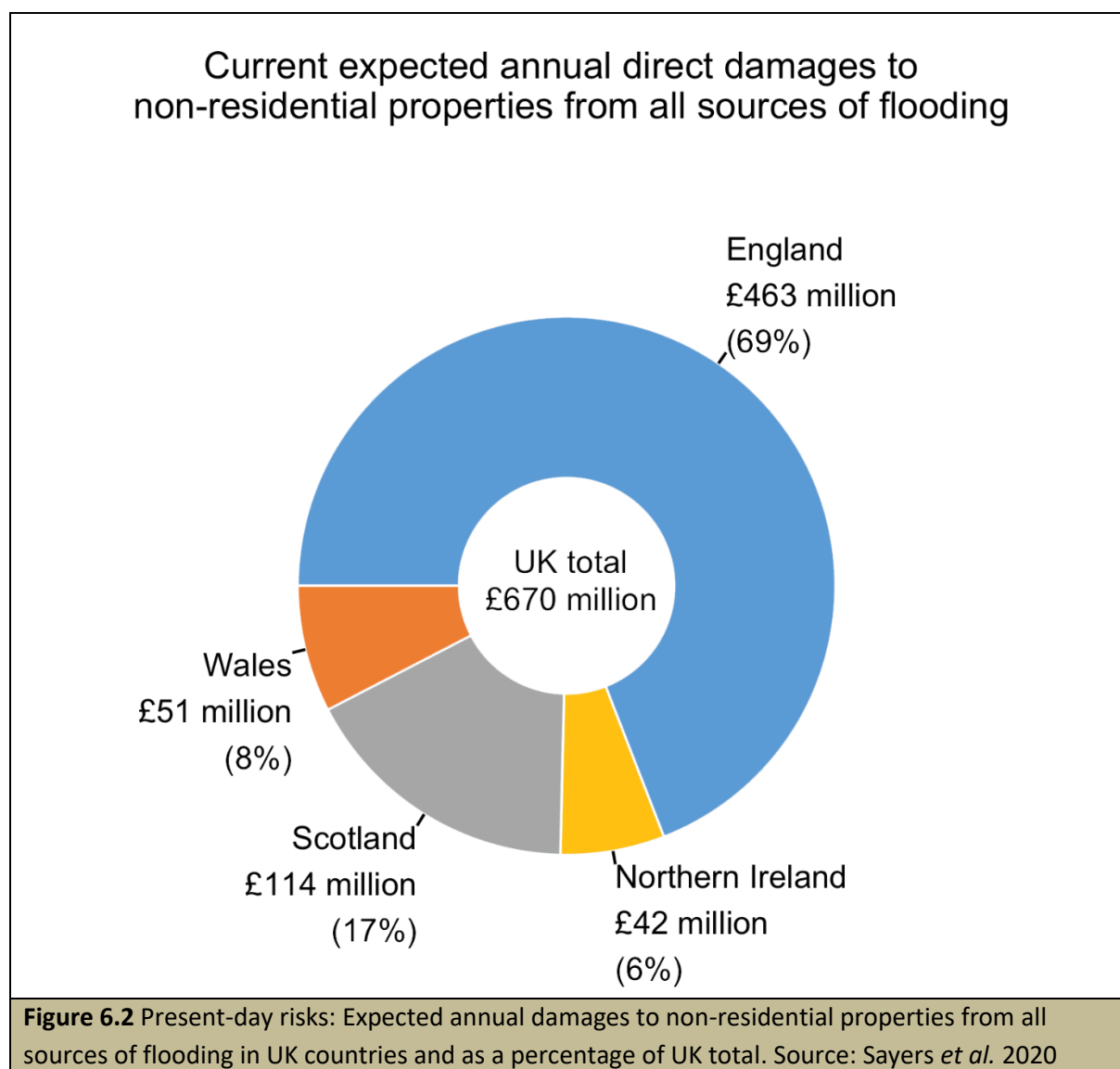
### 6.2.1 Current and future level of risk (B1)

#### 6.2.1.1 Current risk (B1)

##### 6.2.1.1.1 Current risk - UK-wide

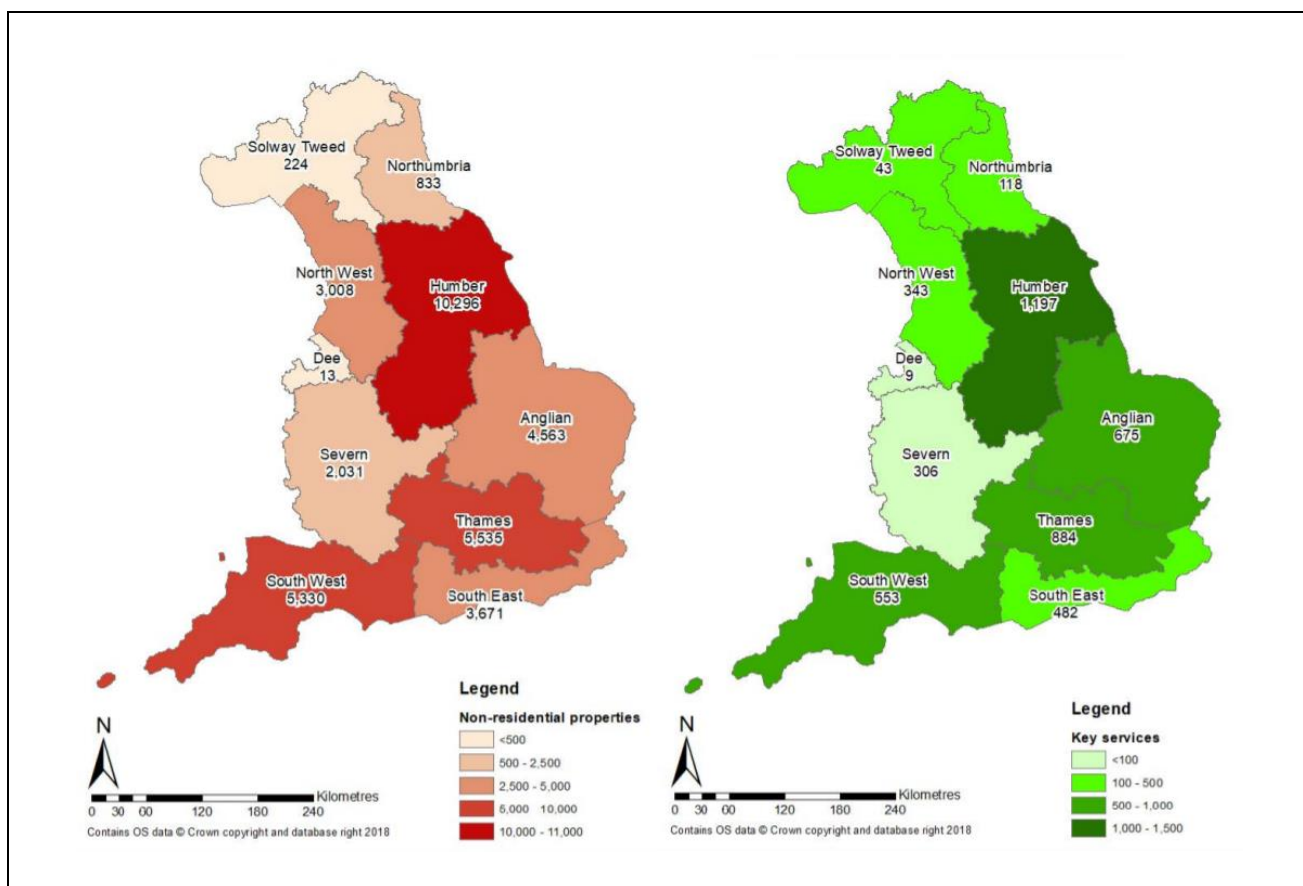
Sayers *et al.* (2020) provides bespoke projections of flood risk to support CCRA3. The projections estimate expected average annual direct damages for non-residential properties from all sources of flooding across the UK; these are outlined in Figure 6.2 to give a sense of the magnitude of impacts on businesses from flooding at present, demonstrating risk with no additional action on adaptation ('Reduced Whole System' adaptation). The total present day expected annual direct damages to non-residential properties from all sources of flooding in the UK is £670 million.

For indirect damages to businesses due to loss of infrastructure Koks *et al.* (2019) use geospatial information on the location of electricity infrastructure assets and local industrial areas and employ a multiregional supply-use model of the UK economy that traces the impacts of floods of different return intervals across 37 subnational regions of the UK. The results show up to a 300% increase in total economic losses when power outages are included, compared to analysis that just includes the economic impacts of business interruption due to flooded business premises. This increase indicates that risk studies that do not include failure of critical infrastructures may be underestimating the total losses – see also Chapter 4 (Jaroszweski, Wood and Chapman, 2021).



#### 6.2.1.1.2 Current risk - England

Sayers *et al.* (2020) report that the expected direct annual damages for non-residential properties in England at present is £463m, comprising 69% of total UK damages, seen in Figure 6.3. The Environment Agency's National Flood Risk Assessment (NaFRA) takes into account the likelihood of flooding and potential consequences including for businesses. The maps below show the variation in risk to the economy across River Basin Districts (RBD) in England for river and sea flooding.



**Figure 6.3** NaFRA assessment of risk to the economy in regions of England. Reproduced from: Environment Agency (2018a), Preliminary Flood Risk Assessment for England, pg. 25 and 26. (a) Number of non-residential properties at high risk of river and sea flooding. (b) Number of key services at high risk of river and sea flooding.

Some evidence is also available by sector; for example, CCC (2018) reported that there are nearly 190,000 ha of Grade 1 and Grade 2 coastal agricultural land at high risk of coastal flooding (1:200 or greater risk) which represents nearly 9% of such land in England.

Box 6.1 presents case study data from the 2015/16 winter floods that impacted several areas across the UK. However, as these estimates quantify exposure but not annual impact, they cannot be used as part of the assessment of current magnitude.

#### Box 6.1 Evidence Arising from the 2015/16 Floods

The winter floods of 2015/16 caused significant damages to businesses and industry in the UK (Marsh *et al.*, 2016). Throughout the winter, flooding impacted communities across northern and western Britain, including some of the UK's major urban centres. Nearly 5,000 businesses across Northumberland, Cumbria, Lancashire, Yorkshire and Greater Manchester were affected by the storms, including the United Biscuits factory and Brunton Park football stadium in Carlisle and the Jorvik Viking Centre in York, a Historic England site. Storm Desmond caused large scale flooding to an area in northern England, particularly Cumbria, which witnessed similar scenes in 2005 and 2009. The flood protection wall in Keswick,

constructed following the 2009 flooding, was overtopped on the 5<sup>th</sup> of December, inundating 730 residential and business properties.

The Association of British Insurers (ABI; 2016) published a figure in January 2016 showing that between December 3, 2015 and January 3, 2016, the insurance response to bad weather and flooding in the UK included £24 million in total spent on emergency payments to households and businesses. This included emergency payments for immediate needs such as food, clothing and salaries; 3,000 families helped into alternative accommodation; £50,000 was the average cost of a domestic property flood claim and more than 8,300 loss adjuster visits were made since December 3, 2015 (high magnitude).

Table 1 shows the estimated economic costs of the 2015 to 2016 winter floods, from the Environment Agency (Environment Agency, 2018b) using ABI claims information. It is estimated that non-residential, direct business property damages from the floods is £513 million (with a range of £410 million to £616 million).

**Box 6.1 Table 1** Estimating the economic costs of the 2015 to 2016 winter floods. Reproduced from Environment Agency (2018)

Flood event	Residential properties					Non-residential, business properties				
	Estimated property numbers damaged by flooding	Best estimate of economic damages (£ million)	Percentage of total economic damages	Average financial cost per property	Average economic cost per property	Estimated property damage by flooding	Best estimate of economic damages (£ million)	Percentage of total economic damages	Average financial cost per property	Average economic cost per property
2015 to 2016 (winter)	16,000	£350	22%	£46,000 £35,000 £24,000	£24,000 £18,000 £12,000	5,000	£513	32%	£153,000	£99,000
2013 to 2014 (winter)	10,500	£320	25%	£44,000	£23,000	3,100	£270	21%	£127,000	£82,000
2007 (summer)	48,000	£1,500	38%	£31,000	£19,000	7,000	£900	23%	£113,000	£75,000

Best estimate of non-residential property damages (£513 million) = ABI non-residential insurance cost + adjustments for underinsurance – economic adjustments.

Where:

- ABI value of residential property claims (£7,540 million) = ABI public data and personal correspondence
- adjustment for underinsurance (£794 million) = £754 million/0.95
- adjustment for economic estimate (£513 million) =  $[(£794 \text{ million} \times 0.45 \times 0.5) + (£794 \text{ million} \times 0.55)]/1.2$
- economic adjustments = VAT 20%, inventory items 45% of insured damages, remaining value 50%
- an average insurance penetration rate for business properties of 95% is assumed

Box 6.1 Table 2 provides a summary of the estimates of economic costs according to different impact categories, including impacts on businesses.

<b>Box 6.1 Table 2</b> Estimates of the economic costs of the 2015 to 2016 winter floods by impact category with uncertainty rating and estimate range. Reproduced from Environment Agency (2018b)				
<b>Impact category</b>	<b>Best estimate (£ million)</b>	<b>Low (£ million)</b>	<b>High (£ million)</b>	<b>Uncertainty rating</b>
Residential properties	£350	£308	£392	Medium to low
businesses	£513	£410	£616	Medium to low
Temporary accommodation	£37	£31	£43	Medium to low
Vehicles, boats, caravans	£36	£31	£41	Medium to low
Local authorities (excluding roads)	£73	£55	£92	Medium to high
Emergency services	£3	£3	£3	Medium to low
Flood management asset and service	£71	£63	£78	Low
Utilities – energy	£83	£75	£91	Low
Utilities - water	£21	£16	£26	Medium to high
Transport - rail	£121	£103	£139	Low
Transport - roads	£220	£166	£275	Medium to high
Agriculture	£7	£6	£8	Medium to low
Health	£43	£32	£54	High
Education	£4	£3	£5	High
Other (wildlife, heritage and tourism)	£19	£13	£25	High
<b>Total</b>	<b>£1.6 billion</b>	<b>£1.3 billion</b>	<b>£1.9 billion</b>	

It is notable that in the 2015 to 2016 floods business property damages were significantly larger than household property damages (a pattern not normally seen in previous estimates of flood damage) – resulting in damage to premises, equipment and fittings, loss of stock, and disruption of business. In the overall scale of costs, the 2015 to 2016 floods at £1.6 billion are similar to the £1.3 billion of the 2013 to 2014 winter floods. The 2007 floods remain, by some margin, the largest economically with costs of £3.9 billion (all in 2015 prices). (Environment Agency 2018b).

#### 6.2.1.1.3 Current risk - Northern Ireland

Sayers *et al.* (2020) report that the expected direct annual damages for non-residential properties in Northern Ireland at present is £42m, comprising of 6% of total UK damages. The Northern Ireland Flood Risk Assessment (NIFRA) (2018) assessed the areas to be at the greatest flood risk in Northern Ireland and the economic impact of such floods (Table 6.4). Note that the percentage changes reported by Sayers *et al.* (2020) may not represent percentage changes relative to the data in Table

6.4 due to methodological differences. The Sayers et al. (2020) changes use a consistent approach across all UK countries.

**Table 6.4** Economic impact of floods. Reproduced from: Northern Ireland Flood Risk Assessment NIFRA. (2018). p.32

	Fluvial	Coastal	Pluvial	Totals
<b>Total Property Damages (Millions)</b>	£10.69	£3.45	£41.83	£55.97
Residential Property Damages (Millions)	£4.32	£0.79	£17.31	£22.42
Intangibles (Millions)*	£0.27	£0.01	£0.40	£0.68
Non-Residential Property Damages (Millions)	£6.10	£2.65	£24.12	£32.87
People at Risk	3359	173	5035	8567
Count Residential	1344	69	2013	3426
Count Non-Residential	321	81	546	948
Count Key Infrastructure	37	7	85	129
Count IPPC	2	1	4	7
Count Cultural Heritage	30	8	83	121
Count Environment	1	0	1	2

\*intangible damages take into account the stress or inconvenience of moving elsewhere whilst a home is repaired after a flood event. For the NIFRA 2018, a constant £200 economic impact per residential property has been assumed.

Some case study information is also available for the North West Flooding event in August 2017 in Northern Ireland (DFI, TEO and DCSDC, 2018), where 60-70mm of rain, equivalent to 63% of the average August rainfall, fell in the space of 8-9 hours causing many watercourses to rise, in some areas, to unprecedented levels in a very short period of time. The severe flooding had a profound, and in many cases lasting, impact on businesses, but no quantification of the business impacts has been made. Impacts to agricultural land were also very significant due to large amounts of debris being washed onto the land. 220 farm businesses were impacted, and fences were washed away in many locations. Issues were raised in relation to businesses being unable to claim for hardship payments similar to those provided to homeowners. In terms of lessons learned, a review of emergency plans and business continuity plans has been recommended, as well as clarification of roles, responsibilities and hierarchy of command before, during and after floods (DFI, TEO and DCSDC, 2018).

#### 6.2.1.1.4 Current risk - Scotland

Sayers *et al.* (2020) report that the expected direct annual damages for non-residential properties in Scotland at present is £114m, comprising of 17% of total UK damages.

SEPA (the Scottish Environment Protection Agency) have developed a data visualisation tool which enables viewers to view statistics from the 2018 National Flood Risk Assessment (SEPA), identify the location of areas with the highest levels of risk (Potentially Vulnerable Areas), locate where flooding has previously been reported and view actions aimed at reducing the impact of flooding. It shows



that around 30,000 buildings of businesses and industry were at flood risk with medium likelihood and around 10,000 buildings of businesses and industry faced flood risk with high likelihood. Importantly the number of properties at risks gives a sense of the scale of risk, but it cannot be used to quantify current magnitude as the number of businesses actually flooded per year is not collected by this means (SEPA 2018).

In Scotland, in early December 2015, severe flooding affected the south of the country with Hawick and Dumfries both badly affected. Late December saw further periods of heavy rainfall that brought more flooding to the South of Scotland, badly affecting Peebles and Newton Stewart. Severe flooding also affected the North-East of Scotland in late December 2015 and early January 2016. Some flooding was experienced in Aberdeen city, but most flooding and associated disruption was experienced across Aberdeenshire, in small towns, villages and the open countryside (CREW, 2020). In North East Scotland specifically, the impact of the winter 2015/16 flooding on business was explored in a 2020 CREW report looking at case studies in Ballater and Garioch. In Garioch, it was primarily residential areas that were flooded in January 2016. In contrast, the impacts of the flooding on businesses operating in and around Ballater were more widespread and more severe. As widely reported in the local press (e.g., Press & Journal, January 6th 2016), numerous shops and other commercial premises in the centre of Ballater were inundated by flood waters, agricultural land and forestry were under water and subsequently littered with debris that had to be cleared up and the damage to the main road network disrupted transportation for many weeks after water levels had subsided (CREW, 2020).

#### 6.2.1.1.5 Current risk - Wales

Sayers *et al.* (2020) report that the expected direct annual damages for non-residential properties in Wales at present is £51m, comprising 8% of total UK damages.

Wales produces River Basin Management Plans, and the following risk data comes from the preliminary flood risk assessments which were published by Natural Resources Wales in December 2018: businesses come under a category of non-residential property along with public buildings such as schools and hospitals. This assessment shows the current number of non-residential properties at risk from river, sea, surface flooding for Dee (870 non-residential properties), Severn (4795 non-residential properties) and Western Wales (5180 non-residential properties). The above numbers don't account for risks to infrastructure sites, which local businesses rely on (341 infrastructure sites at Dee, 1658 infrastructure sites at Severn, and 1658 infrastructure sites at Western Wales).

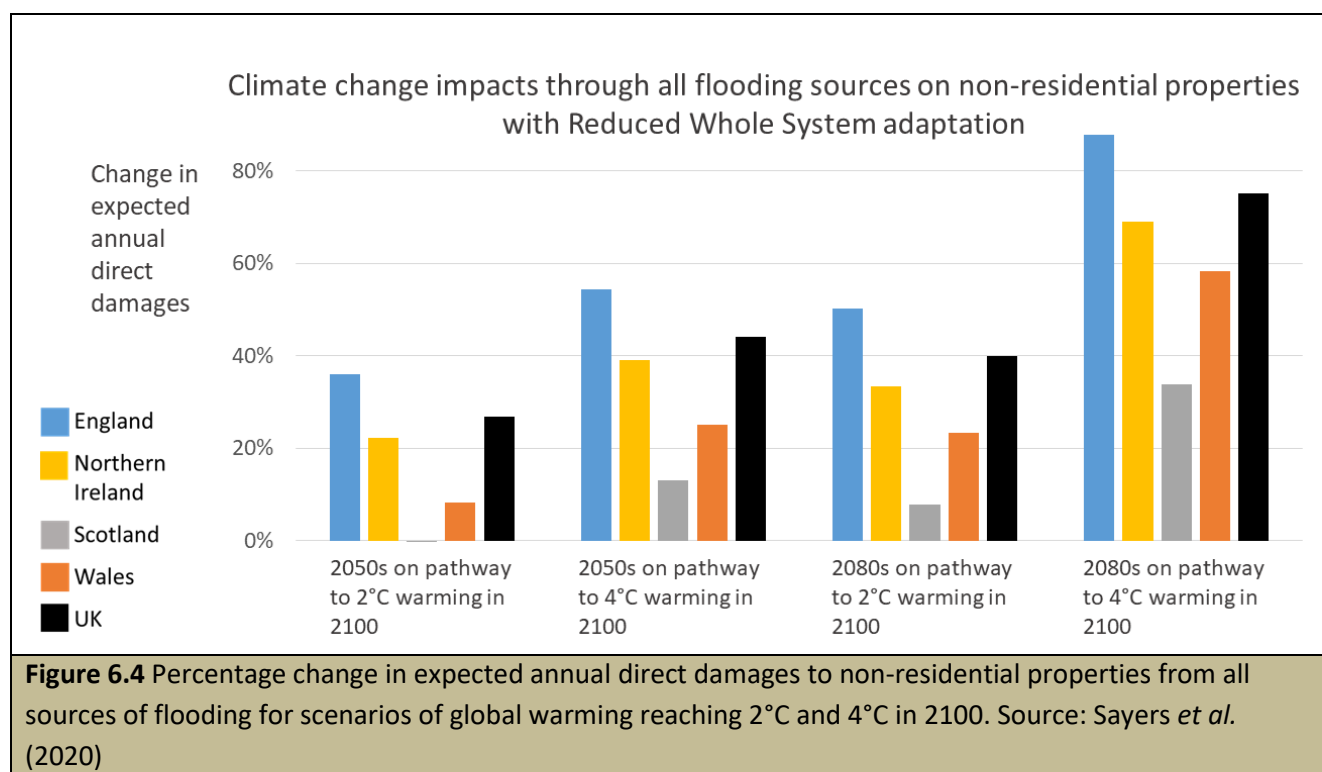
#### 6.2.1.2 Future risk (B1)

##### 6.2.1.2.1 Future risk - UK-wide

Sayers *et al.* (2020) estimate increases in expected annual damages for non-residential properties across the UK at risk from all sources of flooding, for the 2050s and 2080s in scenarios of global

warming reaching 2°C and 4°C in 2100<sup>5</sup> (Figure 6.4). For conciseness these are referred to as the 2°C warming scenario and 4°C warming scenario below.

These estimates assume that the future economy is the same as today and thus are potential underestimates of future damage<sup>6</sup>. The analysis suggests that, without further action, flood risk could significantly increase for many of those business premises by the middle of the century. In the 2°C warming scenario, the expected annual damages for non-residential properties in the UK overall are projected to increase by 27% by 2050 and 40% by 2080. In the 4°C warming scenario, the projected increase is 44% by 2050 and 75% by 2080. This is calculated using the Reduced Whole System model showing risk in the absence of adaptation (there is no difference in risk between the two population scenarios). Note that these projections are single estimates representing one regional climate outcome consistent with the stated warming pathway, so do not represent the implications of uncertainties in regional climate responses, which may be substantial (Chapter 1: Slingo, 2021). Uncertainties in projected changes in exceedance of a flood-related threshold for pathways to 2°C and 4°C warming are presented by Arnell *et al.* (2021).



#### 6.2.1.2.2 Future risk - England

Sayers *et al.* (2020) report that with Reduced Whole System adaptation (i.e. no additional adaptation), the expected annual damages for non-residential properties in England are projected to

<sup>5</sup> Using subsets of UKCP18 probabilistic projections reaching global warming of  $2.0 \pm 0.1^\circ$  and  $4.0 \pm 0.1^\circ$  in the 2090s, relative to 1850-1900, and sea level rise rates within the range consistent with these rates of warming.

<sup>6</sup> Economic growth, and the increase in the value at risk, has a major influence on future total damage costs from flooding (Rojas *et al.*, 2013).

increase by 36% by 2050 and 50% by 2080 in the 2°C warming scenario and increase by 54% by 2050 and 88% by 2080 in the 4°C warming scenario (Figure 6.4).

#### 6.2.1.2.3 Future risk - Northern Ireland

Sayers *et al.* (2020) report that with no additional adaptation, the expected annual damages for non-residential properties in Northern Ireland are projected to increase by 22% by 2050 and 33% by 2080 in the 2°C warming scenario and increase by 39% by 2050 and 69% by 2080 in the 4°C warming scenario (Figure 6.4).

#### 6.2.1.2.4 Future risk - Scotland

Sayers *et al.* (2020) report that with no additional adaptation, the expected annual damages for non-residential properties in Scotland are not projected to increase by 2050 and are projected to increase by 8% by 2080 in the 2°C warming scenario and increase by 13% by 2050 and 34% by 2080 in the 4°C warming scenario (Figure 6.4).

#### 6.2.1.2.5 Future risk - Wales

Sayers *et al.* (2020) report that with no additional adaptation, the expected annual damages for non-residential properties in Wales are projected to increase by 8% by 2050 and 23% by 2080 in the 2°C warming scenario and increase by 25% by 2050 and 58% by 2080 in the 4°C warming scenario (Figure 6.4).

### 6.2.1.3 Lock-in and thresholds (B1)

#### 6.2.1.3.1 Are there lock-in risks?

Business investment decisions taken now— notably around buildings and infrastructure assets – face potential risks if future climate change is not considered. As highlighted in Chapter 5 (Kovats and Brisley, 2021), this is a particular risk if development continues to occur on floodplains and where flood risk management measures are currently or will become insufficient to manage risks. A new study (Roezer and Surminski, 2021) uses a new detailed dataset combining information from Ordnance Survey (OS) and the Office for National Statistics (ONS) to analyse the location of new developments built between 2008 and 2018 in England and Wales in regard to their flood risk. The analysis looks into temporal, spatial as well as sectoral trends and indicates both a sectoral and spatial concentration in a few key areas with implications for the long-term flood resilience in those areas. The initial results (Roezer and Surminski, 2021) focus on impacts on residential properties but a follow-up analysis of at-risk business premises is expected to be available for CCRA4.

In the case where businesses are investing in their own flood protection, there is also a risk of possible lock-in if companies do not consider future flood trends, rendering their efforts inadequate and requiring costly upgrades. Similarly, there could be an over-reliance on hard engineering solutions, which can skew adaptation efforts away from more holistic approaches such as ecosystem services, which tend to have a longer run-up time than immediate heavy engineering solutions. Lack

of awareness, experience and trust in this 'green infrastructure' or 'nature-based-solutions' is a challenge (Surminski and Szoenyi, 2019). However, it is also important to note that ecosystem services may not be as effective for extreme events but can help alleviate the more regular types of flooding (Dadson *et al.*, 2017).

Non-reporting or non-assessment of indirect risks and their implications for business performance, productivity and asset values means that risk levels are underestimated and that there is a lack of urgency for action.

#### 6.2.1.3.2 Are there potential thresholds? (B1)

There are thresholds associated with design and engineering for flood protection infrastructure (see also Chapter 4: Jaroszweski, Wood and Chapman, 2021), and business decision thresholds in terms of acceptable risk or investment criteria (see also Chapter 5: Kovats and Brisley, 2021). Thresholds are likely to vary by time and place depending on the state of the assets, levels of investment to address climate change risks and/or maintain or improve assets, and the spatial changes of risks. As per Power *et al.* (2020), businesses surveyed in their study identified flood risk thresholds determined by property values, cost of insurance, cost of capital, and flood protection schemes not being maintained, failing or not performing as expected. Anticipated asset life threshold must also be considered, as the asset life of a retail premises is much shorter than that of a car manufacturing plant or a pharmaceutical manufacturing complex. For this replaceability of assets can also play a role: for example, offices or a call centre operation could be closed down and restored in a new location immediately if planning is in place, as might banking infrastructure with multiple locations. In contrast, a chemical manufacturing plant cannot be simply replicated in multiple locations and any relocation decisions are likely to be lengthier and more complex than in the servicing sectors.

#### 6.2.1.4 Cross-cutting risks and inter-dependencies (B1)

Even if business premises are not directly exposed to flood risk, the operations can still be negatively impacted by risk cascading through value chains, supply networks and infrastructure dependencies. WSP Global *et al.* (2020) identified a number of cross-cutting risks and interdependencies related to flooding of non-residential properties. The most significant of these pathways are through dependency on infrastructure (see also Chapter 4: Jaroszweski, 2021): flooding of power infrastructure, water and sewage infrastructure, and transport hubs can lead to productivity losses. This also includes the significant environmental threat associated with industrial assets being flooded and this leading to further impacts on natural capital or third parties. Examples are the release of toxic chemicals to water courses, urban areas, long term ground contamination, and loss of productive agricultural land. This is also further explored for supply chains and distribution networks in Risk B6.

## 6.2.1.5 Implications of Net Zero (B1)

Most flood defences have high-embodied carbon, which could be a factor for a Net Zero transition unless a shift to carbon-free building materials is achieved. For public flood defences, the Environment Agency has developed a Carbon Planning Tool for England to assess carbon over the whole life of built assets (Chapter 5: Kovats and Brisley, 2021). The private sector is unlikely to contribute to large scale flood management (unless part of public private partnerships, see below), but there could still be some implications from localised flood management investments. This might influence the type of protection (from hard to soft, or grey to green).

At the same time, the Net Zero transition provides an opportunity for the retrofit of properties – and design of new commercial properties - to improve flood resilience in combination with enhancing energy efficiency. For a discussion of the role of building regulations, see Chapter 5 (Kovats and Brisley, 2021). Realising any Net-Zero opportunities will require increasing awareness amongst business and industry throughout the supply chain as well as upskilling within the sector.

## 6.2.1.5 Magnitude scores (B1)

<b>Table 6.5</b> Magnitude scores for risks to business sites from flooding following different global mean temperature increase projections					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Low confidence)	High  (Low confidence)
<b>Northern Ireland</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Low confidence)	High  (Low confidence)
<b>Scotland</b>	High  (high confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Low confidence)	High  (Low confidence)
<b>Wales</b>	High  (high confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Low confidence)	High  (Low confidence)

Given the expected annual impacts identified by Sayers *et al.* 2020 – (in the £hundreds of millions for England and £tens of millions for the devolved administrations) the magnitude of this risk is high.

This is also supported by other evidence. However, the results from Sayers *et al.* (2020) must be caveated as damages to non-residential properties have relatively high uncertainty due to difficulties in categorising property types. For example, approximately a third of the EAD in NaFRA2018 for England is attributed to "non-classified" properties. This uncertainty is accounted for in the confidence of the findings. It is also important to note that the Sayers estimates do not include future economic growth; they assume that business sites and functions are the same as today.

## 6.2.2 Extent to which current adaptation will manage the risk or opportunity (B1)

### 6.2.2.1 Effects of current adaptation policy and commitments on current and future risks (B1)

#### 6.2.2.1.1 UK wide

Across all parts of the UK there are investments and policies in place aimed at reducing flood risk that also protect businesses and infrastructure. These are also set out in detail in Chapter 5 (Kovats and Brisley, 2021. Risk H3). Level of implementation, selection of target areas as well as performance and maintenance of these interventions remains difficult to assess consistently across the whole of the UK. A dedicated project to assess future flood risk across the UK to support CCRA3, Sayers *et al.* 2020, considered the impact of a scenario reflecting the current level of policy ambition to manage flooding across the UK and reported that the expected annual damages for non-residential properties in the UK overall are projected to increase by around 10% by 2050 and 17% by 2080 given the current level of adaptation, with a 2°C warming scenario. With the 4°C warming scenario, this increase is 23% by 2050 and 42% by 2080.

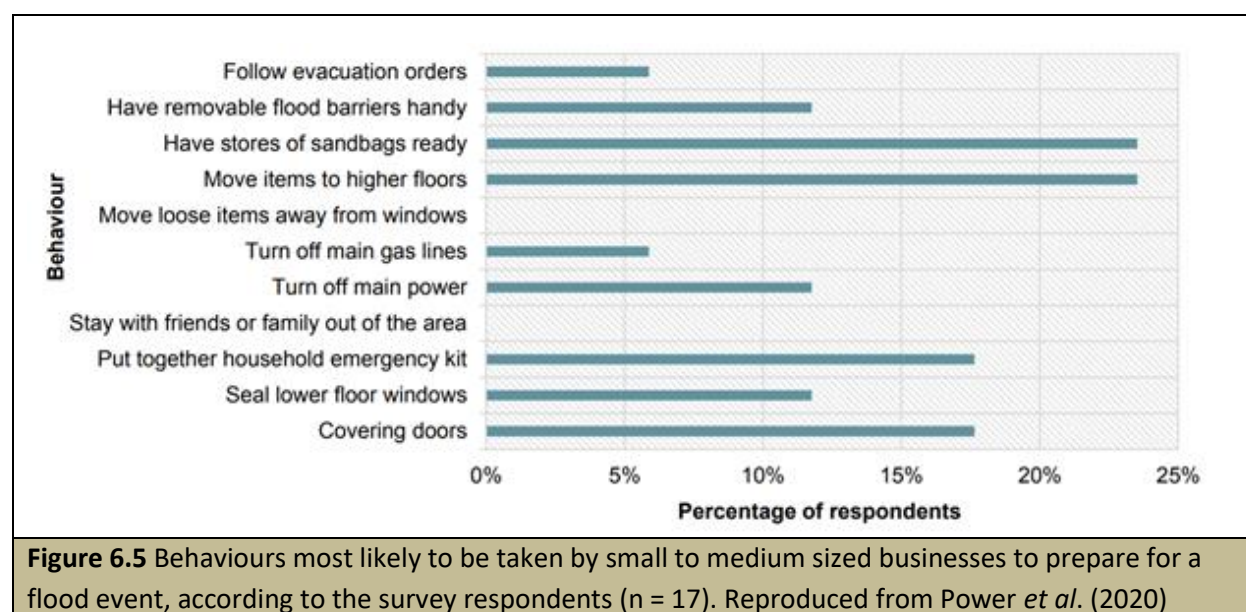
Across the UK the changes are summarised as below (Sayers *et al.* 2020):

- **England:** the expected annual damages for non-residential properties are projected to increase by 17% by 2050 and 25% by 2080 in the 2°C warming scenario, and by 31% by 2050 and by 51% by 2080 in the 4°C warming scenario.
- **Northern Ireland:** expected annual damages for non-residential properties are expected to increase by 18% by 2050 and 28% by 2080 in the 2°C warming scenario and by 33% by 2050 and 55% by 2080 under a 4°C scenario.
- **Scotland:** there is a decrease in expected annual damages of -15% by 2050 and -11% by 2080 in the 2°C warming scenario and by -6% by 2050, but an increase by 8% in the 4°C warming scenario.
- **Wales:** there is a decrease by -7% in 2050 and increase by 2% in 2080 in expected annual damages for non-residential properties, in the 2°C warming scenario and an increase of 3% by 2050 and 23% by 2080 in a 4°C scenario.

These values are calculated using the Current Level of Adaptation scenario showing risk with planned level of adaptation efforts at the time Sayers report was completed, taking account of information in the National Flood and Coastal Erosion Risk Management Strategy for England (Environment Agency, 2020b) and the Flood and coastal erosion risk management Policy Statement (HM Government, 2020). It is important to note that even with this adaptation in place, there are

still significant levels of residual damages (albeit lower than without these measures as in 6.6), and a significant increase in flood damages relative to current conditions.

Power *et al.* (2020) found that the most common behaviours that SMEs take to prepare for a flood event were having stores of sandbags ready (24%) and moving items to higher floors (24%). Automated voice messaging systems, text alerts and government websites were shown to be the most commonly used sources of information about flooding events by small to medium sized businesses. Less than 20% of SMEs surveyed had taken any permanent protective measures (Figure 6.5).



In the LSE Climate Risk Business Survey (2020) companies reported a set of adaptation measures that they have implemented in response to flood risk – as summarized in Table 6.6.

Respondents also identified which information sources on flood risk have helped them develop their risk management strategies, with in-house expertise and consultants, industry or sector-wide reports and Government guidance featuring as the top three sources. (LSE Climate Risk Business Survey 2020 – Matthews and Surminski, 2020).

An example of sectoral activities aimed at facilitating business-level adaptation to flood risk is the property flood resilience (PFR) Bonfield (2016) action plan (resulting from the PFR Roundtable of businesses) which set out how businesses can protect themselves from flood damages. The report (Defra, 2016) made recommendations to make flood resilient measures part of ‘normal’ business practice. Actions included developing a ‘health check’ for small businesses (e.g., assessing whether adequate insurance cover is in place) and providing case studies of successful flood resilient measures and associated costs/benefits. To date there is a lack of evidence that the voluntary code of practice has led to an increase in the uptake of Property Flood Resilience by businesses, as further investigation will only be possible once the Code of Practice has been fully adopted and applied by companies. There have also been initiatives by the Business in the Community Initiative and AVIVA to create guidance around flood preparedness for businesses (BITC and Aviva, 2020).

**Table 6.6** Business responses to flood risk (Source: LSE Climate Risk Business Survey 2020 – Matthews and Surminski, 2020)

<b>Adaptation strategies</b>	<b>Number of companies who have implemented these in response to flood risk</b>
Investing in ecosystem-services / green solutions to reduce risks, e.g. natural water storage/drainage, green roofs, tree planting	23
Investing in 'hard' engineering solutions e.g. upgrades to flood protection, new water saving devices, heat reduction in offices	30
Developing and implementing enhanced business continuity plans that consider current and future risks including regular reviews and tests	25
Using early-warning systems to increase preparedness	10
Engaging with staff to increase awareness, preparedness and identify solutions	26
Adopting adaptation standards (e.g. ISO)	11
Working with suppliers e.g. requiring evidence of climate resilience measures, collaboration to strengthen supply chains	13
Changing type of products or services	14
Adjusting production processes	4
Buying more insurance	5
Avoiding high risk locations, materials, suppliers or investments	6
Engaging with government and/or regulators to receive information and guidance	23
Don't know	3
None	8
Other	1

Although efforts to promote PFR have had some success, it is not used sufficiently in refurbishment/post-flood reinstatement. Based on uptake in properties supported under the grant in aid investment, PFR is used by just 6% of high-risk households, 39% of flooded households and 15% of flooded businesses (Harries, 2013; Bhattacharya-Mis *et al.* 2014). It should be noted that properties have been supported via targeted PFR repair schemes that have been deployed on a handful of occasions since 2013/2014 after a flood event to enable households and businesses to build back better. As these schemes are delivered through Local Authorities, Government does not have accurate figures on the numbers of properties supported.

#### 6.2.2.1.2 England

The recent government announcements and policies on flood risk management are summarised in Chapter 5, Risk H3 (Kovats and Brisley, 2021). The policy direction suggests a greater focus on a portfolio of measures to improve resilience and greater recognition of future flood risk levels (Surminski, Merhyar, Golnaraghi, 2020). In addition to spending on flood defences, the new



government flood risk and coastal erosion policy statement for England (Environment Agency, 2020b) and the flood and coastal erosion risk management Policy Statement (HM Government, 2020) committed to increasing the uptake of property level flood resilience in homes and businesses, as well as other approaches to adaptation such as nature-based solutions, flood resilient design and sustainable drainage systems (see Chapter 5. Risk H3: Kovats and Brisley, 2021).

As reported in the CCRA2 Evidence Report, the CCC has identified evidence of more systematic planning for a range of climate change risks including flood risk for large businesses, but there is little evidence of planning or implementation of flood adaptation by SMEs. Much of the support and advice services available in the past in England no longer exist (CCC, 2019a). While information and advice is available, for example via Regional Flood and Coastal Committees, the uptake of these resources remains unclear. However, some Local Enterprise Partnerships (LEP) facilitate Central Government provided grants and loans for projects or businesses that enable economic growth and job creation by reducing the risk of flooding to land or operations. These have also emerged as investors in Financial Risk Management (FRM) projects that support these outcomes, such as in the East Coast towns of Ipswich, Great Yarmouth and Lowestoft (over £20m of grants and loans).

A public-private partnership funding approach to reduce flood risk is also promoted by the UK Government and requires the private sector to contribute to flood protection and risk management investments. One example is the Bacton to Walcott Coastal Management Landscaping Project (see also Chapter 3, Risk N17: Berry and Brown, 2021), where the majority of funding originated from the private sector. Through this project, the height and width of the beaches have been increased and access to beaches improved (North Norfolk District Council, 2019). Similarly, the Canvey Island Multi-agency Partnership (MAP) was formed to raise flood risk awareness and increase resilience of Canvey Island's communities and businesses to flooding (Environment Agency et al, 2015). This was a partnership between Anglian Water, Castle Point Borough Council, the Environment Agency and Essex County Council (including Essex Highways).

Other examples are the Willerby and Derringham Flood Alleviation Scheme and River Aire Flood Alleviation Scheme and other examples where the private sector has contributed, e.g., Nestlé and the Lower Dove Flood Alleviation Scheme (Alexander *et al.* 2016), and collaboration between Hull City Council and local water company.<sup>7</sup> However, this has also created challenges – with some stakeholders arguing that these schemes incentivise local council to grant planning permissions in high-risk areas in order to secure private sector funding for flood risk management (CCRA3 stakeholder discussions). Moreover, the partnership funding approach does not provide any obligation for the private sectors to contribute, and it is up to the Lead Local Flood Authority (LLFA) to present a business case for a voluntary contribution, which in some cases is the main challenge in attracting private funding contributions. This is particularly the case for coastal flooding where FRM infrastructure costs and the density of business assets are higher, meaning partnership funding gaps are typically greater (Surminski, Mehryar and Golnaraghi, 2020).

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<sup>7</sup> <https://www.hullccnews.co.uk/24/06/2019/hull-leads-the-way-in-how-to-tackle-threat-of-flooding/>

Defra is also funding three Pathfinder projects in Yorkshire, the South West and South Midlands between 2018 and 2021 to engage more businesses in flood resilience both from a precautionary point of view as an investment opportunity.

Examples of business-level adaptation include firm flood investment in Cumbria following Storm Desmond in 2015. As per Cumbria LEP (2020), a Cumbrian manufacturing firm invested £2.6m (benefiting from Cumbria Local Enterprise Partnership) to protect its premises from flooding. The new flood protection measures are designed to offer protection from a '1 in 1000' flood event and consist of a flood wall around the firm's production buildings.

Multi-sectoral collaboration is still relatively low in England but there are pilot projects at the local level that aim towards more integration of local businesses in local flood risk planning and decision making. One example is the engagement of the Zurich Flood Resilience Alliance in Lowestoft, Suffolk, where the local government is working with Alliance partners to increase understanding of risk and resilience across different segments of society, including businesses.

#### 6.2.2.1.3 Northern Ireland

Recent assessments and policy announcements on managing flood risk in Northern Ireland are set out in Chapter 5 Risk H3 (Kovats and Brisley 2021).

The second Northern Ireland Climate Change Adaptation Programme (NICCAP2) includes references to flooding as being one of the major risks to businesses in Northern Ireland, and highlights that unlike the rest of the UK, SMEs make up the vast majority (99.9%) of the total number of businesses in Northern Ireland. The programme mentions the role of Invest Northern Ireland (the regional economic development agency for Northern Ireland) in providing guidance to businesses on adaptation. It also provides property support across a range of business parks in Northern Ireland in determining design features of these developments. It also seeks early engagement with statutory bodies over its plans in order to reduce the risk of flooding. Despite this, Invest Northern Ireland accepts that in the future some of its business parks may fall victim to incidents of flooding and with that there will be implications for it as the landlord and for its tenants (NICCAP2).

Invest Northern Ireland also offers a free service, [nibusinessinfo.co.uk](http://nibusinessinfo.co.uk), which is described as the official online channel for business advice and guidance in Northern Ireland. The service encourages businesses to assess their potential risk of flooding and provides a link to the River Agency's flood map. There is also a guide for sustainable drainage systems and suggestions for good practice.

#### 6.2.2.1.3 Scotland

Flood risk management policy in Scotland is summarised in Chapter 5, Risk H3 (Kovats and Brisley, 2021).

The Scottish Government is investing £420 million over ten years (2017 to 2027), with 42 Flood Protection Schemes or engineering works scheduled to begin between 2016 and 2021 to improve protection for 10,000 properties, though no estimate is given of the number of businesses

protected. Specifically in relation to businesses, Scotland's second Scottish Climate Change Adaptation Programme (SCCAP2) contains actions related to support business resilience to flooding, including guidance provided by Adaptation Scotland, flood forecasting and warning services, updated flood maps and the development of a property flood resilience action plan.

Other initiatives include a Property Flood Resilience Delivery Group (PFRDG) where members will work with multi-sector specialists and key stakeholders to identify and deliver actions that need to be taken to engage the public and the construction and insurance industries with PFR; and a living with flooding action plan which recommends actions for a range of stakeholders, including businesses, to take to help promote property flood resilience in Scotland.

The Scottish Flood Forum is funded by the Scottish Government (£193,000 in 2020-21) to provide recovery and resilience support to businesses including post flooding support, advice on property level protection and on business continuity. SEPA's Floodline business page can help businesses to identify if they are at risk of flooding and prepare accordingly. However, if and how this is applied by businesses when considering site location decisions remains unclear.

The Scottish Government is also preparing a policy document: 'Water Resilient Places – A Policy Framework for Surface Water Management and Blue-Green Infrastructure' that they plan to launch in early 2021 (not yet published at the time of writing). It aims to improve how to manage surface water flooding by complementing and supporting existing policy and organisational responsibilities as set out in the Flood Risk Management (Scotland) Act 2009. The policy objectives aim to make surface water management relevant to all sectors and make it a core consideration in designing for climate adaptation, sustainable place-making and 'delivering great blue-green places to live'.

#### 6.2.2.1.4 Wales

Flood and coastal erosion risk management policy in Wales is covered in detail in Risk H3 (Chapter 5: Kovats and Brisley, 2021). Overall, £144 million has been invested in managing flood risk over five years (2016 to 2021). Natural Resources Wales and local authorities are managing risks to businesses as part of their overall strategic response to managing flood risks to communities. Risks to businesses have been identified across Wales and this was recognised in Prosperity for All: A Climate Conscious Wales, Welsh Government's national adaptation plan. This includes actions to:

- Do more to understand the risks to business from infrastructure disruption and higher working temperatures; and
- Provide support to businesses to help them adapt to the future risks from climate change.

The plan commits to increase research and understanding of the risk to business, while also updating guidance and the provision of 1-2-1 support to businesses wishing to work on adaptation. A Climate Change Adaptation Tool exists in Wales to support businesses in the tourism sector from risks including flood. Welsh Government's climate adaptation plan, Prosperity for All: A Climate Conscious Wales commits to renewing the tool, expanding further into businesses around the historic environment and using it as a blueprint to support tools for other sectors.

The Wales Flood and Coastal Erosion Risk Management Strategy (Welsh FCERM, 2020) sets the overall policy framework for Local Flood Management Strategies delivered through Natural Resources Wales (NRW) and local authorities, by recognising coastal impacts on habitats and species from flooding and erosion and highlights efforts to introduce interventions which use natural systems to reduce negative impacts. The strategy tends to refer to businesses alongside households and communities as a collective, but there are some important points in the strategy from a business perspective including a case study of the Pontarddulais Flood Alleviation Scheme which is protecting 22 businesses; a commitment from NRW to provide more detailed information on the numbers of businesses at risk; and a £150 million Coastal Risk Management Programme aimed at protecting vulnerable businesses within coastal communities around Wales (Welsh FCERM, 2020).

Delivery of FCERM is supported through Shoreline Management Plans, as well as the 'Communities at Risk' Register that provides a consistent way of considering and ranking flood risk from all sources based on the FRAW. In addition, Area Statements for local collaboration planning, stakeholder engagement and action on Sustainable Management of Natural Resources (SMNR), including flood risk management have been developed, but levels of business involvement are unclear. The Welsh Government Consultation on the post-EU Welsh land management scheme focuses on climate mitigation, whereas adaptation and climate risk is only referenced in relation to meeting carbon targets and in the context of flood risk. Post-EU Welsh land management scheme changes to farm payments will potentially focus on supporting farmers for flood risk management (Welsh Government, 2019a).

#### 6.2.2.2 Effects of non-government adaptation (B1)

Evidence on actions by non-government actors are included in the sections on the extent of adaptation underway above, as private-sector investment in flood risk mitigation is part of government strategies. These include action to prevent flood damage by installing flood resistance and resilience measures. Resilience measures are fitted inside a property to reduce damage once flooding has occurred (e.g., internal design such as raising electrical sockets), and resistance measures aim to prevent floodwater from entering a building. Other adaptation measures are also possible such as retrofitting, through climate-smart operation and maintenance procedures, and by increasing preparedness and resilience (flood alerts, flood emergency response plans, insurance). There are various barriers to private-sector adaptation (see below) which suggest that government intervention continues to be needed.

#### 6.2.2.3 Adaptation shortfall (B1)

The term 'Adaptation Shortfall' is used across CCRA3 to describe the difference between actual and possible adaptation, capturing the existing 'adaptation gap' in the UK. The extent to which the interventions summarised above will help to control flood risk to businesses remains unclear, largely due to a lack of evidence from across the UK on business' readiness for flooding, especially within SMEs. However, it is important to recognise that investments in large-scale flood protections will take time to materialise and will never completely remove flood risk. Therefore, it should be kept in mind that flood protection is never absolute and may even create a false sense of security, as it tends to stop other complementary risk reduction and adaptation activities from going ahead.

Considering the concept of residual risk, including the potential failure or breach of flood defences, it is important to continue with holistic resilience efforts, including property-level protection measures and nature-based solutions. This portfolio approach is recognised across all of the national flood and coastal erosion risk management policies in the UK.

Although the evidence above shows that much activity is underway, our view is that given the rising risks from climate change additional measures to support business adaptation and an enhancement of existing plans and actions is required.

There is a lack of national, climate change scenario-driven future flood risk maps, though progress is being made with some regional level analysis such as through the new National Flood Risk Assessments for England and Wales emerging. There is a lack of evidence to show the rate of uptake of Property Flood Resilience (PFR) installations and other resilience measures by businesses. Earlier feedback from flood protection manufacturers suggests overall uptake of property-level resilience measures by businesses is relatively low, in England at least (CCC, 2015), though there has potentially been support through PFR repair schemes after major flood events (CCC, 2019a). Wragg, McEwan and Harries. (2015) suggest that business adaptation to flood risk is a neglected area and that an information 'hub' for businesses will enable sign-posting to advisory sources, 'science communication', and support for those suffering the trauma of damage to their premises and livelihoods. At the moment, guidance and advice are provided separately by each UK nation (and advice and support services have closed in England). There is no single plan or information source to guide people, communities and businesses during their recovery from flooding. Whilst there are many organisations that are managing different parts of the system, further integration of plans could streamline this advice and make it easier to access.

Our engagement with insurance industry stakeholders as part of the UKCCRA3 stakeholder discussions highlight that price signals remain inadequate in signalling risk to businesses. This means businesses underinvest in flood resilience measures. In particular, where there is lack of previous flood history, and provision of relatively inexpensive flood insurance cover, there are few incentives for businesses to change risk-taking behaviour. The need to further reform the planning system was also raised in stakeholder discussions in the insurance sector. For instance, it was suggested that the National Planning Policy Framework (NPPF) and planning guidance on the Design Flood (planning standards) need to include the flood profiles to be modelled to 1 in 500 risks of climate change. Moreover, it was suggested that the 'safe for its design life' definition be rewritten in accordance with this modelling. The government policy statement commits to review the current approach to flood resilient design to consider how to ensure quality, safe housing.

#### 6.2.2.4 What are the barriers preventing adaptation? (B1)

There are a number of barriers and constraints to private sector adaptation action, which make it difficult for businesses to plan and implement adaptation actions. As noted in CCRA2 and analysed in Cimato and Mullan (2010) and Frontier *et al.*, (2013), adaptation to changing flood risks requires a mix of action from businesses and government. The stakeholder discussions that were held during the CCRA3 process (see section 6.15) highlight that there can be confusion about risk ownership and

roles and responsibilities between public and private sector, with companies expecting government action and vice versa. This applies to all risks in this chapter. Importantly, the uptake of any measures is dependent on motivation of businesses and available incentives to make businesses realise the positive benefits of undertaking properly level measures if their business is at risk of flooding. A survey of the UK's 122 largest businesses shows that more than half of the UK's biggest companies have done little or no work to adapt to climate change, although two-thirds recognise that climate change poses a short- to medium-term risk to their business. Small and medium-sized enterprises, which account for more than 60% of employees in the UK, are likely to be less prepared to deal with climate change effects than larger companies. (Chartered IIA, 2020).

There are other barriers that can hamper action, even when it is clear that action is needed. They include:

- Uncertainty, which translates through to the market failure of imperfect information (or in cases asymmetric information or moral hazard).
- An expectation that insurance or government support will carry the costs. Recent investments in flood protection schemes, while reducing risks from one type of flooding for a specific location, could also create a false sense of security. Protection does not replace the need to adapt, particularly with regards to indirect risks from flooding.
- Adaptation actions have a public goods or non-market dimension that the private sector is unlikely to invest in as they do not present immediate returns.
- The available capacity and resources to adapt are often an issue, especially for private sector investment decisions, as the internal rate of return on adaptation will be low compared to other areas.
- Terminologies can also pose issues – with many businesses not familiar with 'adaptation' and instead using other terms, including 'resilience' (see Section 6.13).
- Lock-in can arise due to site location decisions that disregard future risk trends.

These aspects underline the role for government to intervene as a regulator, by creating the regulatory framework which is conducive to adaptation and resilience, and as a funder of important adaptation public goods such as flood defence, which require large capital investment, as well as to act (similarly) to help address the potential risks of indirect effects (flooding of infrastructure and transport disruption).

#### 6.2.2.5 Adaptation scores (B1)

<b>Table 6.7</b> Adaptation scores for risks to business sites from flooding			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)

### 6.2.3 Benefits of further adaptation action in the next five years (B1)

Given our assessment above, our view is that there will be significant benefits from further action in the next five years from low-regret actions to improve the evidence base and provide further awareness raising, advice and support to businesses to improve their resilience to flooding. Quantifying risks and impacts is difficult, particularly for individual business sectors, where data is often commercially sensitive. However, Sayers *et al.* (2020) report that if further adaptation measures are taken, in addition to what is currently planned then the UK-wide expected annual damages for non-residential properties could decrease by up to 21% increase by 2080. Results are calculated under the Enhanced Whole System model.

Businesses could also make use of the flood forecasting and warning services provided by the Environment Agency, Natural Resources Wales and SEPA, in conjunction with the Met Office, to plan for and respond to flooding in their areas. In terms of government support, stakeholder engagement indicates that investing in 3D interactive models for commercial properties would be beneficial for data collection. Whilst this will require significant government investment, insurance companies alone are unlikely to bear the upfront costs. It is likely that improving the uptake of property flood protection by businesses will have significant benefits in the next five years, though further data are required to understand this and the current level of uptake specifically in the context of SMEs.

#### 6.2.3.1 Indicative costs and benefits of additional adaptation (B1)

The overall benefits of further investment in flood management for commercial property through the reduction in expected annual damages are estimated by Sayers *et al.* (2020). This study does not estimate the costs of these measures, and thus does not undertake a cost-benefit analysis, but the literature in general reports high benefit to cost ratios from such investment (Rojas *et al.*, 2013; Ward *et al.*, 2017).

There are some low regret activities where Government can act to enhance adaptation in the private sector. The uptake of adaptation measures by businesses is relatively low, with small businesses particularly at risk: only a quarter of businesses with fewer than 10 employees have continuity plans for extreme weather (in GOS and Foresight, 2017). This despite the fact that such plans are a cost-effective adaptation measure: around four-fifths of businesses with continuity plans in place report that the benefits of having a plan exceed the costs of producing one. There is, therefore, a role for raising awareness on climate risks (flood alerts) and providing relevant information and response planning. There is now a reasonable evidence base on the costs and benefits of property resilience and resistance measures for households (Environment Agency, 2015; Wood Plc 2019). These found that a number of flood resilience and resistance measures could be considered no-regret adaptation measures (i.e., a benefit to cost ratio of greater than one in cases where there is a greater than 1% chance of Annual Exceedance Probability, AEP). In general, this literature reports that all measures are more expensive if retrofitted rather than installed in new builds. For resistance measures, the difference between costs of retrofitting vs. incorporating into new builds are more modest. However, the applicability of each of these measures depends on the type of flooding (recurrence and depth), as this alters the relative cost-effectiveness (and benefit to

cost ratio). While there is less data on the costs and benefits of similar measures for commercial properties, it is likely that similar findings of low-regret adaptation opportunities apply. There is also some wider literature on the benefits of blue and green infrastructure in alleviating direct and indirect damages from flooding to industry and infrastructure, using the city of Newcastle as a case study (Blue-Green Cities Project, 2016). This assessed the benefits of sustainable urban drainage on water flow, sediment dynamics and flood risk in fluvial systems. Given the residual damage costs even with current flood management policy (Sayers et al., 2020) this is clearly an area where there are benefits of future action, and in many cases these benefits are projected to outweigh the costs.

### 6.2.3.2 Overall urgency scores (B1)

<b>Table 6.8</b> Urgency scores: Risks to business sites from flooding				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency Score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Medium	Medium	Medium

Given the magnitude of current and future flood risks across all parts of the UK, and the assessment that the risk will only be partially managed in future, more action is needed both with regards to corporate adaptation and implementation of public policy to support businesses to adapt. Lock-ins are a particular concern as there is evidence that current business decisions are leading to increased exposure.

### 6.2.4 Looking ahead (B1)

Our view based on the assessment above is that businesses across the UK and across sectors are focusing on current rather than future location risks. There are gaps in understanding suitability of location-focused flood resilience measures. It is therefore important that planned and ongoing research and pathfinder schemes collaborate with business and consider business needs and requirements. Public – private partnership approaches can help improve preparedness and resilience in businesses. Furthermore, we see evidence that partnership approaches between businesses can help provide localised adaptation and can complement some of the national schemes. However, it is unlikely that private sector adaptation alone will suffice (see barriers section). Therefore, it is important to direct some tangible measures including financial incentives towards business flood risk management, particularly for SMEs across the UK.



## 6.3 Risks to business locations and infrastructure from coastal change (B2)

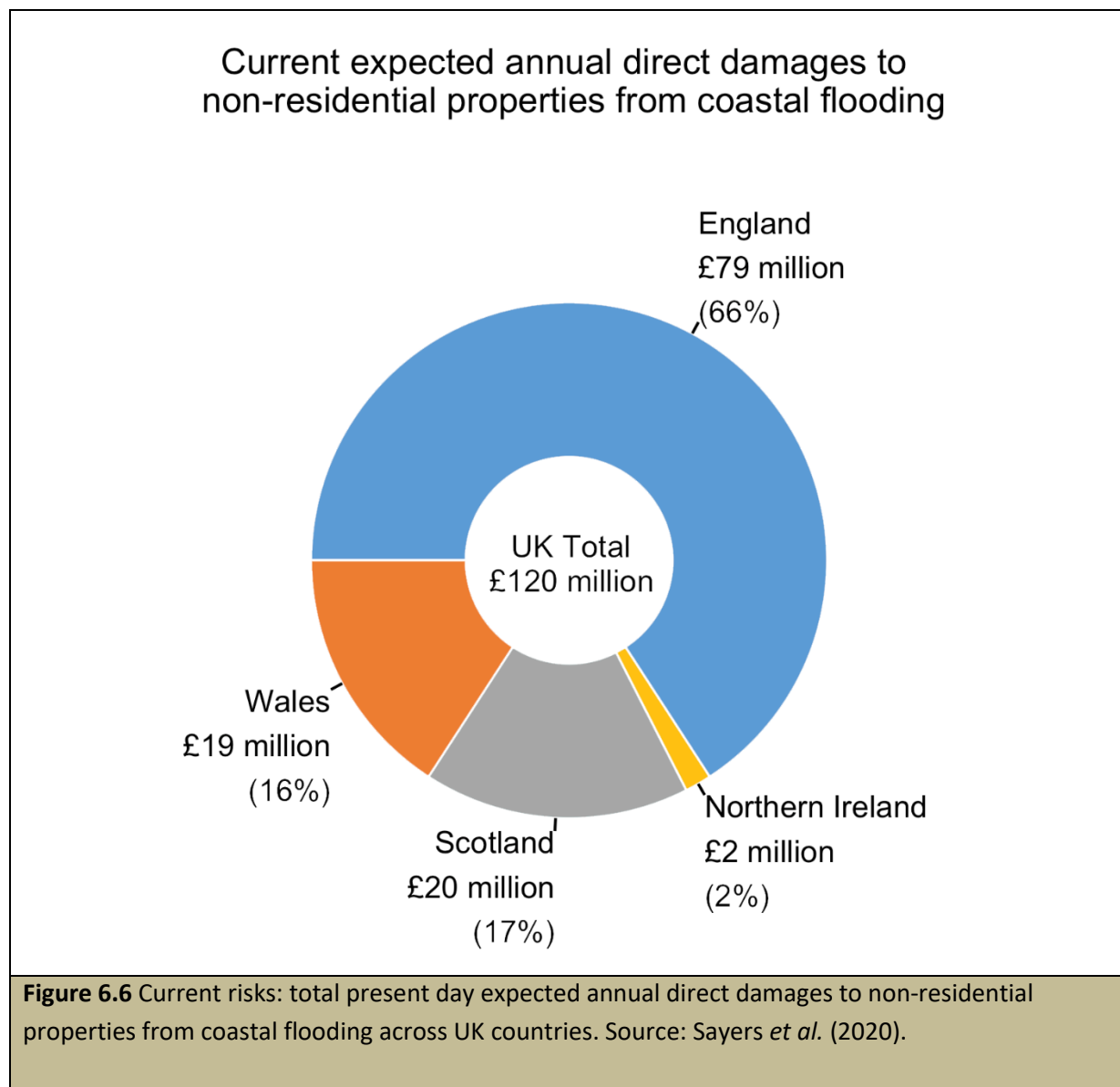
For most of the UK, a considerable amount of industrial and commercial activity occurs along the coast, while significant infrastructure is also located in coastal areas (the risks to infrastructure are outlined in Chapter 4: Jaroszweski, Wood and Chapman, 2021). The type and level of risk to businesses and business-related infrastructure along the coast depends on the geomorphology of the coastline, the coastal processes; nature of the hazard; past human interventions in the coast; and the coastal protection policy currently implemented. All of these are affected by sea level rise, the uncertainties associated with it, and the amplifying impact it has on the risks of coastal flooding due to extreme high tides, storm surges and/or fluvial flooding in tidal rivers and estuaries, as well as erosion. Coastal change across the UK therefore is posing a high risk to businesses now and is expected to remain a high risk in the future. However, there is a significant diversity of levels of information about climate risks and adaptations for the four UK nations which makes a comparison of adaptation difficult. For England, Scotland and Wales, evidence is growing on the changing risks and adaptations being used in the form of risk assessments and shoreline management plans, though we found a lack of similar information for Northern Ireland. UK wide, cascading risks for businesses arising from the failure of critical infrastructures after flood damage are increasingly recognised but there is no centralised evidence base that can be easily accessed. Thresholds associated with risk from coastal change include design and engineering thresholds for coastal flood protection infrastructure and business decision thresholds for levels of acceptable risk or investment criteria. Across all parts of the UK more action is needed to respond to the rising levels of risk.

### 6.3.1 Current and future level of risk or opportunity (B2)

#### 6.3.1.1 Current risk (or opportunity) (B2)

##### 6.3.1.1.1 Current risk - UK-wide (B2)

The current impact to coastal business locations is mainly driven by coastal flooding and extreme weather events such as the major storms of 2013/14 affecting southern England and floods in 2015-16 in northern England and southern Scotland. Sayers *et al.* (2020) provides estimates of expected annual damages for non-residential properties from coastal flooding by UK country; these are outlined below to give a sense of the magnitude of the risk to businesses from flooding at present, demonstrating risk in the absence of adaptation. The total present day expected annual direct damages to non-residential properties from coastal flooding in the UK is £120 million. A breakdown by region can be found in Figure 6.6.



In comparison, the current risk data for impacts on businesses from coastal erosion is quite limited but growing. For example, Masselink *et al.* (2020) state that “a large proportion of the coastline of the UK and Ireland is currently suffering from erosion (17% in the UK; 19.9% in Ireland)” (Masselink *et al.*, 2020: 158). However, there is significant regional disparity in the quality and depth of understanding of coastal risks for businesses across the UK.

#### 6.3.1.1.2 Current risk - England and Wales

The CCC’s Coastal Change Report highlights that there is a total of 144,985 non-residential properties within Flood Zone 3 in England, which represents the present day 1:200 (0.5%) year risk from coastal flooding. For coastal erosion the CCRA2 Evidence Report and the CCC’s report on coastal adaptation (CCC 2018) reported that around a third of the English coastline is already experiencing impacts of erosion, with Masselink *et al.*, 2020 reporting that “of the 3,700 km

coastline of England (and Wales), 28% is experiencing erosion greater than 10 cm per year, which can be exacerbated by heavy or prolonged rainfall, coastal storms or sea-level rise.” (Masselink *et al.*, 2020)

#### 6.3.1.1.3 Current risk - Northern Ireland

Northern Ireland faces major and increasing risks from coastal erosion and coastal flooding, however due to a lack of baseline evidence on coastal structure and processes it is difficult to assess this (see also The Irish News, 2018). There is a lack of both historical coastal change data and risk information for coastal businesses and infrastructure in Northern Ireland, limiting the potential for effective preparatory decision making: Rates of coastal change, the effects of storms, the seasonal behaviour of the coast, interactions between beaches and dunes, and the possible impact of coastal structures are not known (Cooper and Jackson, 2018).

#### 6.3.1.1.4 Current risk - Scotland

Dynamic Coast, Scotland’s National Coastal Change Assessment (NCCA), has mapped the physical susceptibility of the coast and identifies that soft coastline (i.e., coasts with the potential to erode) makes up 19% (3802 km) of the coast (Hansom *et al.*, 2017). The NCCA estimates that between a half and a third of all coastal buildings, roads, rail and water network lie in these sections subject to erosion (In Scotland, 78% of the coast is considered ‘hard or mixed’, and is unlikely to erode at perceptible rates, 19% is ‘soft/erodible’, whilst 3% has artificial protection. Since the 1970s, 77% of the soft/erodible coast in Scotland has remained stable, 11% has accreted seawards and 12% has eroded landwards” (Masselink *et al.*, 2020). Where coastal changes occur, the NCCA identifies: (i) nationally average erosion rates around the Scottish coastline have doubled since the 1970s to 1.0 metre per year and (ii) accretion rates have almost doubled to 1.5 metres per year (Masselink *et al.*, 2020).

#### 6.3.1.2 Future risk (B2)

##### 6.3.1.2.1 UK-wide

The impacts from coastal flooding and erosion on business assets such as industrial plants (such as chemical processing plants) and factories (such as food processing facilities, pharmaceutical manufacturing), roads, railways, train stations, power stations, landfill sites and farmland, are expected to increase across the UK, as highlighted by recent climate change projections, including potential Low likelihood, high impact scenarios (High ++ or extreme sea level rise scenarios) suggesting that sea levels could rise by more than 1 metre by 2100. Further details are given in Chapter 1 (Slingo, 2021) and in the coastal context, in Chapter 5 (Kovats and Brisley, 2021). These include potential scenarios of very high future sea level rise, that would lead to significantly larger impacts than those used below in association with 4°C global warming by the late 21<sup>st</sup> Century.

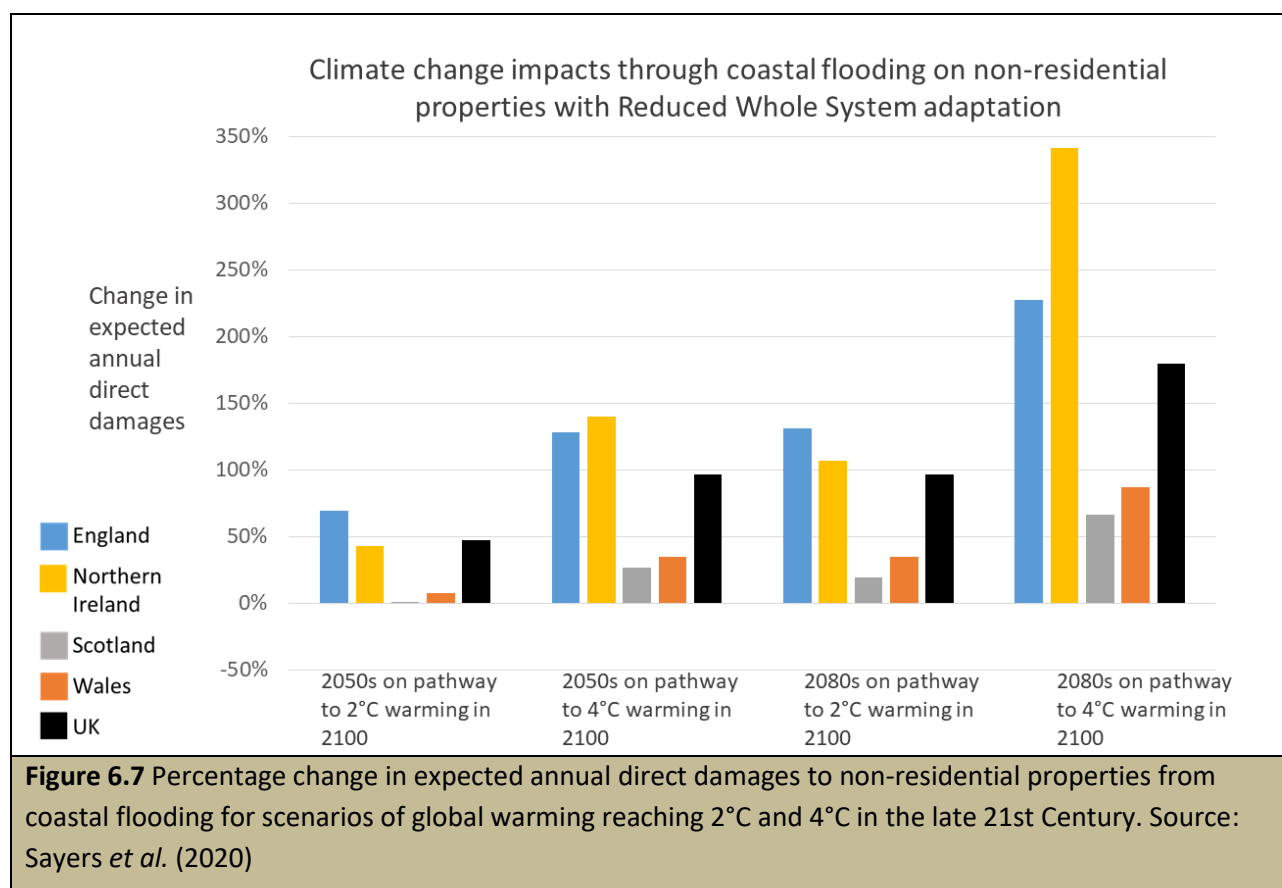
Sayers *et al.* (2020) estimates the following increases in expected annual damages for non-residential properties across the UK that will be at risk from coastal flooding in the 2050s and 2080s,

for scenarios of sea level rise associated 2°C and 4°C global warming by the late 21<sup>st</sup> Century<sup>8</sup> (Figure 6.7). For conciseness these are referred to here as 2°C and 4°C warming scenarios, although it should be noted that a wider range of sea level rise rates could also result from these rates of warming.

Sayers *et al.* (2020) report that with the 2°C warming scenario, the expected annual damages for UK-wide non-residential properties from coastal flooding is projected to increase by 47% by 2050 and 97% by 2080 on the basis of no additional adaptation. With the 4°C warming scenario, the increase is projected to be 97% by 2050 and 179% by 2080. These do not assume future economic growth, and thus are potential underestimates of future value at risk and damages.

Based on the Sayers *et al.* (2020) estimate of a 179% increase in damages by 2080 in the 4°C warming scenario, annual costs could increase from £120M to £336 Million for 2080.

This is calculated using the Reduced Whole System model showing risk in the absence of adaptation. A regional breakdown can be found in Figure 6.7.



Recent figures from Mandel *et al.* (2020) calculate the overall direct and total impact induced by an extreme (95<sup>th</sup> percentile) UK coastal flood event (yearly damages) measured in basis points (0.01%) of World Gross Domestic Product (GDP). Losses are calculated for the financial and private sectors following a shock for two scenarios for socioeconomic and climate dynamics: First, a scenario with

<sup>8</sup> Using subsets of UKCP18 sea level rise projections within the range consistent with scenarios of global warming of  $2.0 \pm 0.1^\circ$  and  $4.0 \pm 0.1^\circ$  in the 2090s, relative to 1850-1900.

rapid and emission intensive economic growth, i.e., combining SSP 5 and RCP 8.5 and a second scenario with low-carbon and sustainable economic growth, i.e. combining SSP 1 and RCP 2.6. (Mandel *et al.*, 2020). Whilst the average financial propagation of shocks amplifies risks by a factor of 2 for most countries, for the UK, the amplification ratio can reach a factor of 10 in a high-impact scenario without adaptation. The UK is therefore listed under the ten most impacted countries, in their study, due to coastal flood risks and its role as a global financial hub (Risk B4).

Ballinger and Dodds (2017) suggested that businesses operating in a coastal environment and facing a change in the coastal management designation from protected to unprotected are likely to experience significant challenges including: loss of value of capital assets located in that coastal area, inability to access financing to relocate out of the blighted coastal area, and potentially complete business failure. Infrastructure providers in the same context potentially face complete loss of coastal access roads, and high costs of decommissioning existing coastal infrastructure to remove any potential for harm from degraded assets.

Heritage businesses which rely on access to seaside resorts are also expected to be impacted: As well as the impact of coastal change on these assets and local businesses they support, there is also potential for maladaptation arising from clean-up operations and flood protection measures. Impacts on the historic environment are also expected to cause economic difficulties in Scotland, where the heritage sector generates £4.2bn for Scotland's economy, with many businesses in these areas strongly connected to the cultural heritage of the places (Historic Scotland, 2020).

Cascading risks from the failure of critical infrastructures after flood damage are increasingly recognised. Chapter 4 (Jaroszweski, Wood and Chapman, 2021) provides a deeper look at this, including the impact of cascading failures and the example of the consequences Storm Desmond had on Lancaster due to the flooding of substations. Within the seafood industry, alongside the known risks of changes in storms and waves, and changes in ocean temperature, emerging risks come from ocean acidification and de-oxygenation of the seas which are explored further in Chapter 3.

Sectoral impacts include the marine leisure industry (MCCIP 2014). Coastal marinas are multi-faceted profit centres that are potentially highly vulnerable to climate change impacts (e.g., storms, sea-level rise and flood risk affecting asset values and occupancy). This could be an issue for older sites if they become unleaseable due to adverse weather events. Rising insurance costs could mean that getting cover for both site and boat owners becomes more difficult (MCCIP 2014).

The port industry (Asariotis *et al.*, 2017) is also at risk from extreme events. Damages could arise from impacts on port infrastructure/cargo from incremental and/or catastrophic inundation and wave regime changes; higher port construction/maintenance costs; potential modulation of tides causing sedimentation/dredging in port/navigation channels and operational timetable changes; effects on key transit points; increased risks for coastal road/railway links; relocation of people/businesses; and insurance issues (Asariotis *et al.*, 2017). For ports, incremental sea level rise is also a significant issue. Many of the UK's ports and jetties will require costly improvements to accommodate a 1m sea level rise (see Chapter 4: Jaroszweski, Wood and Chapman, 2021). With increased high tides and without adaptation, it could become more challenging to moor and load/unload ships, due to inability to secure the ship due to mooring and fender heights. Further

issues might arise from the inability of loading cranes to service ships as they will be higher and from the inability of loading arms (oil, chemical, gas, grain products) to attach to ships at high tide (Becker *et al.*, 2018).

Gibson *et al.* (2020) project impacts of extreme events in the coastal community of Torbay 20, 50 and 100 years ahead, showing significant local differences in the risk to the tourism and hotel industries and the resulting economic impacts.

Within the seafood sector, the main current and future risks are perceived to be alteration of ocean ecosystems; changing catch potential; regional shifts in stock distribution and increased severity of storms and flooding (Garret *et al.*, 2015), with impacts on port infrastructures (Garret *et al.*, 2017; Garret *et al.*, 2018). This can also lead to a loss of product refrigeration due to interrupted / disrupted electricity supply leading to product spoilage/damage, but the scale has not yet been assessed for the UK. The potential implications of these changes are damaging impacts on the national economy through declining fisheries and more localised impacts on employment, which are explored further in Chapter 3 (Berry and Brown, 2021).

#### 6.3.1.3 Lock-in and thresholds (B2)

##### 6.3.1.3.1 Are there lock-in risks?

Business investment decisions have a high potential for lock-in for this risk, because of the location of investment and the rising risks of coastal flooding and coastal erosion. Business investment decisions with long lifetimes taken in the next decade or two— notably in the context of buildings and infrastructure assets – face potential risks if future climate change is not considered or if businesses do not have access to available information including on coastal erosion from local authorities. Lock-in risks related to coastal change include:

- Defra (2018) find that there is a risk for maladaptation where private defences undertaken by business owners may not always offer expected benefits. There is also a concern around how private defences align with the wider Shoreline Management Plans. The report suggests that is fundamental to ensure localised actions do not exacerbate wider risk.
- Attitudes towards the coastal protection and perceptions of longevity of that policy option, mean that businesses may plan for future development based on current protection levels if there is not sufficient community and business engagement in the long-term plans for a specific area, yet these may change.
- Current coastal management policy can lead to the decommissioning of areas, which may be both an opportunity and sizeable loss for coastal business. In our view the business community struggles to appreciate the opportunities involved in re-shaping places and the benefits this might bring to local economy including for tourism. This points towards an engagement challenge and signals that the negative impact on the local economy from coastal change could

also be turned around with some positive imagination of what the place could become with the intelligent application of those policies.

- Furthermore, local economic choices to defend and maintain can ‘blight’ the coastline, and not only lock communities into economic choices that may not be very climate resilient, but also damage economic interests of other communities down the coast (e.g., stopping sediment supply to beaches etc).

#### 6.3.1.3.2 Are there potential thresholds?

A study by Haasnot *et al.*, (2013) investigated the role of thresholds for coastal adaptation, considering thresholds under different sea level trajectories and policy responses. Thresholds included coastal erosion on erodible or soft coastlines and engineering protection standards that would be exceeded beyond a particular risk level. For businesses there can be decision thresholds in terms of acceptable risk levels being exceeded, insurance not being available or experienced damage exceeding a particular magnitude. Businesses may choose to avoid investing in some coastal infrastructure at risk from flooding (Jones *et al.*, 2019), potentially limiting development options for existing businesses and the infrastructure they rely on. Across the UK policy responses and protection investments will influence how soon these thresholds will be met. Coastal management is a devolved issue, whereby decisions about development and rollback options are taken locally. Access to resources for development in coastal areas varies around the UK. This variation in access to funding could become a major threshold for adaptation. In England there are plans to increase council funding through retention of business rates, implying that local tax revenues could become important funding stream for flood and coastal risk management. The impact of moving to the business rates retention scheme could leave many councils in the North out of pocket – with knock-on effects for their ability to fund flood management activities (Hunter, 2019). According to CCC (2018) the application of adaptation pathways focused on the management approach (which can be aligned to SMP policy type) and use of monitoring key thresholds to trigger future management decisions, has benefits over sticking to rigid setting of policy type within defined time-bound epochs as is the case with SMPs. But given local capability, resourcing and funding for coastal management is limited, this may not be practical or feasible.

#### 6.3.1.4 Cross-cutting risks and inter-dependencies (B2)

There are interdependencies in terms of adequacy and performance of infrastructure in coastal locations (see Chapter 4: Jaroszweski, Wood and Chapman, 2021), including a growing recognition of the risk to ports from weather-related disruption (Masselink *et al.*, 2020). For instance, there has been extensive reporting under the Climate Change Adaptation Reporting: second round reports (ARP2) where six harbour authorities and two lighthouse authorities submitted reports. As per the report submitted by the Associated British Ports (ABP), the majority of potential climate impacts are currently considered to be of low risk with a small number of medium-term risks. Key risks identified were related to engineering and vessel traffic service (VTS) functions and the projected impacts associated with sea level rise and flooding, temperature increases and storminess. There are resulting actions proposed which are incorporated in the bodies’ Marine Safety Management

System. ABP's 21 ports around the coast of Britain are estimated to contribute some £5.6 bn to the UK economy every year. To this end, climate risks for ports and their associated hinterland industries and critical infrastructure (e.g., access roads and rail) pose a threat to the UK economy given their contribution to food, fuel, chemicals and electricity generation. Moreover, significant impacts to port infrastructure and associated business impacts could affect a small number of coastal industries that employ large sections of the local workforce (ABP, 2016).

#### 6.3.1.5 Implications of Net Zero (B2)

The same issues apply as for the previous Risk B1. Flood defences have high embodied carbon. This could be a factor for a Net Zero transition and might influence the type of protection (from hard to soft, or grey to green). At the same time, the Net Zero transition provides an opportunity for the retrofit of properties – and design of new commercial properties - to improve flood resilience in combination with enhancing energy efficiency. This requires increasing awareness amongst business and industry as well as upskilling within the sector.

#### 6.3.1.6 Magnitude scores (B2)

<b>Table 6.9</b> Magnitude scores for risks to business locations and infrastructure from coastal change from erosion, flooding and extreme weather events					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	Medium  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Low confidence)	High  (Low confidence)
<b>Northern Ireland</b>	Medium  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Low confidence)	High  (Low confidence)
<b>Scotland</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Low confidence)	High  (Low confidence)
<b>Wales</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Low confidence)	High  (Low confidence)



Note: The magnitude scoring is based primarily on the analysis by Sayers *et al.* 2020 and is ‘medium’ for England and Northern Ireland now, with annual economic damages in the tens of millions today, rising to hundreds of millions for England in the future. For Wales and Scotland the current magnitude is already high, with tens of millions damage today, and expected to increase further in the absence of additional adaptation (see Table 2, Chapter 2 (Watkiss and Betts, 2021) for details of the magnitude scoring)

## 6.3.2 Extent to which the current adaptation will manage the risk or opportunity (B2)

### 6.3.2.1 Effects of current adaptation policy and commitments on current and future risks (B2)

#### 6.3.2.1.1 UK-wide

Since CCRA1 and CCRA2, there have been notable policy changes in relation to managing coastal change: There is growing recognition of trade-offs inherent in meeting coastal management objectives of coastal residents, businesses and nature (e.g. the National Flood and Coastal Erosion Risk Management Strategy for England (Environment Agency, 2020b), the Flood and Coastal Erosion Risk Management Policy Statement (HM Government, 2020); and the Wales Flood and Coastal Erosion Risk Management Strategy (2020-21). Furthermore, we note an increasing focus on the language of resilience in policy documents and implication of a need for coastal businesses to ‘live with’ flooding (e.g., CCC, 2018).

Historically, coastal protection in the UK has typically included: hard engineered protection (e.g., groynes, rock armour, beach nourishment, seawalls, offshore breakwaters etc.); land reclamation and re-engineering (often in estuaries and around ports); soft protection (e.g. dune nourishment, use of wetlands as a coastal buffer); and allowing natural processes of erosion and accretion to occur. Coastal management policy became more formalised through the Shoreline Management Plans of the 1990s. SMPs are non-statutory policy documents that are implemented in England, Wales and Scotland and which inform wider strategic planning.

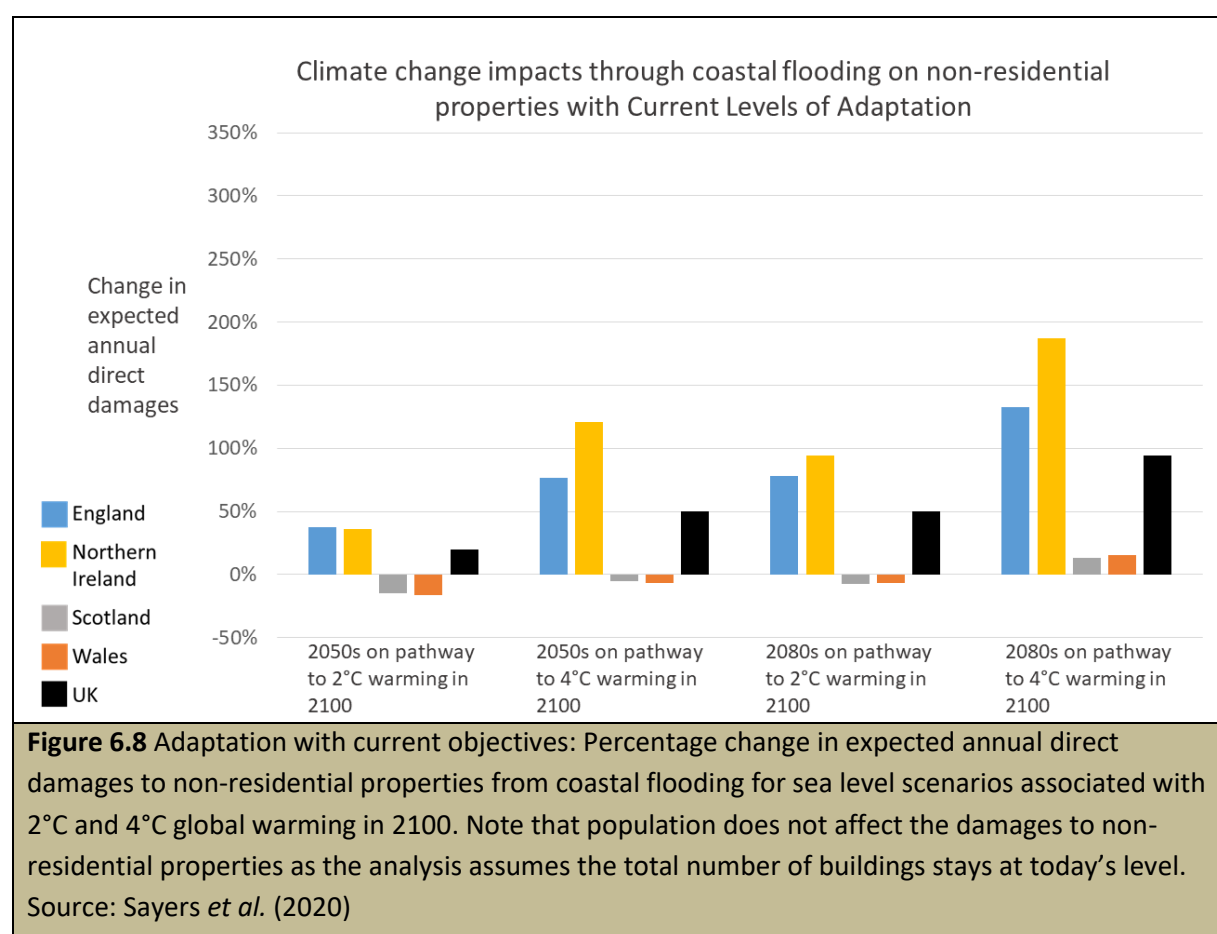
Sayers *et al.* (2020) report that under a scenario of a continued level of current adaptation ambition, the expected annual damages for non-residential properties due to coastal flooding are to increase by 20% by 2050 and 50% by 2080 in the 2°C warming scenario, and by 50% by 2050 and 94% by 2080 in the 4°C warming scenario. These results are UK-wide; regional breakdowns can be seen in Figure 6.8. It should be noted however that the Sayers report did not cover coastal erosion and was concluded before the publication of the National Flood and Coastal Erosion Risk Management Strategy (Environment Agency, 2020b) and the Flood and Coastal Erosion Risk Management Strategy Policy Statement (HM Government, 2020).

Some businesses have undertaken adaptation by

- investing in ‘hard’ engineering solutions e.g., upgrades to flood protection, new water saving devices, heat reduction in offices (Alshebani *et al.*, 2014)

- developing and implementing enhanced business continuity plans that consider current and future risks including regular reviews and tests (Day *et al.* 2018)
- investing in ecosystem-services / green solutions to reduce risks, e.g., natural water storage/drainage, green roofs, tree planting (Lupton, 2018)

Risk B1 in this chapter, and Chapter 5, Risks H3 and H4 (Kovats and Brisley, 2021) set out general policies across the UK to reduce the risks from coastal flooding and erosion, so those are not repeated here. Policies that are specific to coastal flooding/erosion and businesses only are summarised below.



### 6.3.2.1.2 England

In England (as well as in Wales – see below), two rounds of risk-based Shoreline Management Plans (SMPs) have been developed over the last 25 years, covering all coastal areas in England. It should be noted that these have not been developed in a consistent way across England, and the datasets that underpin these SMPs are not consistent in content nor universally available (Ballinger and Dodds, 2017). The first SMPs were completed in 1997; the second round (SMP2) completed in the late 2000s. SMP2s engaged with the public, including businesses and organisations with an interest in this part of the coast to ensure that the SMP dealt with their concerns. An SMP-Refresh (SMP-R) is currently underway, and the Government committed to review national policy for SMPs in its recent

Policy Statement (HM Government, 2020). The SMP-R identifies some key issues relevant for the business community:

- Lack of consistency in technical information available for SMPs, meaning that key sources of information needed for decision making by businesses may not be available.
- Lack of impact, clarity and usability of SMPs, meaning that the content of the SMPs may not be useable by businesses that are planning developments in the coastal zone.

The Government also committed in its Policy Statement to review the current mechanisms that coastal erosion risk management authorities can use to manage the coast and also to explore the availability and role of financial products or services that can help businesses to achieve a managed transition of property and infrastructure away from areas at very high risk of coastal erosion (HM Government, 2020). The National Planning Policy Framework (NPPF) recommends that Local Planning Authorities identify Coastal Change Management Areas (CCMAs) within Local Plans for areas “likely to be affected by coastal change (physical change to the shoreline through erosion, coastal landslip, permanent inundation or coastal accretion)”. The main barriers to CCMA development appear to relate to organisational arrangement, specifically ineffective integration across sectors within the local planning authority. Defra (2018) note a lack of support from councillors of local council policies with respect to adaptation, while CCC (2018) noted that 18% (17 out of 94) of active coastal Local Plans that could refer to an up-to-date SMP do not.

A number of research projects delivered under the Environment Agency’s 2013 framework for Coastal Research, Development and Dissemination have improved understanding of coastal flood and erosion risk and are developing tools to support coastal management (for example the guide to morphological modelling developed in the iCOASST project).

Natural England have developed good practice for managing protected wildlife sites on the coast. The Environment Agency will continue to explore how to value natural capital assets on the coast and use that understanding to help make choices about the best coastal management approaches to take, including possible natural flood and coastal management (see Risk N17 in Chapter 3: Berry and Brown, 2021).

NAP2 (England) acknowledges the risks businesses face from extreme weather but does not set out specific plans to address these risks for businesses alone. Instead, the actions related to flood and coastal erosion risk management in general.

#### 6.3.2.1.3 Northern Ireland

In Northern Ireland, no Shoreline Management Plans have been developed to date. Ad-hoc measures are in place to protect the coastline against flooding and erosion. All reports identify the urgent need for accessible coastal data (processes, beach profiles, wave data etc.) to underpin decision making in Northern Ireland, e.g., see Cooper and Jackson (2018).

The second Northern Ireland Climate Change Adaptation Programme (NICCAP2) draws on the detailed 2018 Baseline Study and Gap Analysis of Coastal Erosion Risk Management NI (Amey

Consulting, 2018) which identifies lack of coastline erosion data and monitoring as a priority to inform future coastal management policy.

#### 6.3.2.1.4 Scotland

To date SMPs have been produced for only short sections of the Scottish coast, though not all areas of the coast are at risk from coastal flooding and erosion. SMPs are in place in six of Scotland's 25 coastal local authorities (Angus, Dumfries & Galloway, East Lothian, Fife, North and South Ayrshire, and Scottish Borders). Dumfries and Galloway is currently updating its SMP.

For the last five years Scotland has focussed on developing a database of coastal change for future coastal planning, through its Dynamic Coast programmes. Dynamic Coast 2, which will conclude in 2021, will give the Scottish Government an up-to date assessment of coastal changes and ability to adapt to future sea level rise providing a robust evidence base for strategic coastal planning.

The second Scottish Climate Change Adaptation Programme 2019-2024 (SCCAP2) (Scottish Government, 2019) builds on the significantly improved data on coastal change generated through Dynamic Coast. Some of the general activities related to adaptation for businesses to coastal change include: improving prospects for marine fisheries and aquaculture, creating resilient harbours, future-proofing coastal buildings and learning to manage flood damage in historic buildings, managing the relocation of some waterfront buildings, and re-establishing coastal processes and habitats to improve coastal resilience.

#### 6.3.2.1.5 Wales

In 2017, the Welsh Government established a Flood and Coastal Erosion Committee to manage issues related to coastal change. The Welsh Government's climate adaptation plan, Prosperity for All: A Climate Conscious Wales (Welsh Government, 2019b) explains how communities, businesses and infrastructure can adapt to the impacts of climate change. For example, it identifies actions to build defences to guard against flooding and coastal erosion; grow more woodland to reduce erosion and protect soil and slow down floods; and create 25,000 more energy efficient homes by 2021. In addition, as described in Section 6.4, the Wales Flood and Coastal Erosion Risk Management Strategy (2020-21) recognises coastal impacts on habitats and species from flooding and erosion and highlights efforts to introduce interventions which use natural systems to reduce negative impacts, with data available via the River Basin Preliminary Flood Risk Reports.

Round six of the Coastal Community Fund will have around £3.7 million available to fund projects that address the unique economic challenges of coastal areas in Wales. Grants between £50,000 and £300,000 are available for a wide range of organisations and businesses which benefit coastal communities in Wales. Applicants for funding are expected to consider the Welsh Government's National Marine Plan. Additionally, the 2-year Coastal Communities Adapting Together (CCAT) project looks at the regional implications of climate change, focussing on the coastal communities of Milford Haven and Pembroke Dock in Wales (as well as communities in Ireland). As part of the project, local people are encouraged to observe, interpret and record data about their community and coastal environment, and to take an active role in adapting their communities and businesses.

Natural Resources Wales is working with other agencies on Shoreline Management Plans which focus among other things on planning for sea level rise and climate change for the next 100 years (see section on England above for a discussion on SMPs that also relates to Wales).

The Wales National Marine Plan has only broad aims for increasing understanding climate risk and climate resilience for the marine environment. However, it does focus on the marine economy and businesses, location, supply chain, aquaculture, renewables fisheries, and marine freight businesses.

Businesses located in Fairbourne in Wales are experiencing the economic and social effects of planned 'decommissioning' coastal protection within the next 40 years. While no actual impacts are being experienced yet, the loss of 'protected' designation means that (i) people in Fairbourne can no longer get mortgages for new premises as Fairbourne is below sea level and will flood without protection; (ii) equity cannot be released from existing businesses to allow a relocation away from Fairbourne (Coastal Partnership East, 2019). A case study on Fairbourne is set out in Chapter 5 (Kovats and Brisley, 2021).

#### 6.3.2.2 Effects of non-government adaptation (B2)

For some sectors there is evidence of action being taken, for example in the fisheries sector, vessel owners are already enhancing operational safety, but may need to keep a watching brief on how climate change is affecting fisheries (see Chapter 3, risks N14 – N16: Berry and Brown, 2021). The trade agreement concluded with the EU in 2020 provides for the transfer of 25% of fishing rights from EU vessels in UK waters to the UK fishing fleet (European Commission, 2020), which should lead to an expansion of the fleet. Longer term, the vulnerability of entire fleets should be assessed. Onshore, port authorities in the UK are investing in actions to build port resilience but should improve risk management. The vulnerability of freight ferries also needs to be assessed. More evidence is needed to identify the rates at which different sectors are autonomously engaging with adaptation action, and the types of actions that are being undertaken. However, overall there remain gaps in understanding across the UK about the business impacts of coastal change, what actions businesses are taking to prepare for climate change, trends in vulnerability and exposure to coastal flooding and coastal erosion, the resilience of infrastructure services including ports and airports, telecoms, digital and ICT, infrastructure interdependencies (see Chapter 4: Jaroszweski, Wood and Chapman, 2021), and opportunities that could be found from innovative forms of adaptation (such as portable beach homes – see below).

#### 6.3.2.3 Is there an adaptation shortfall? (B2)

Although some action is underway, our view is that it will only partially manage the risks to businesses from coastal change according to the evidence available, which is also reflected in the assessments of coastal adaptation shortfall in Chapters 3 (Berry and Brown, 2021), Chapter 4 (Jaroszweski, Wood and Chapman, 2021) and Chapter 5 (Kovats and Brisley, 2021). A continuation of current levels of ambition as set out in the Sayers *et al.* (2020) analysis suggests that expected annual damages to businesses from coastal flooding will not stay at today's level on the basis of current actions, or even in an enhanced adaptation scenario. It should be noted however that the

Sayers report did not cover coastal erosion and was concluded before the publication of the National Flood and Coastal Erosion Risk Management Strategy (Environment Agency, 2020b) and the Flood and Coastal Erosion Risk Management Strategy Policy Statement (HM Government, 2020).

Mandel *et al.* (2020) find that adaptation policy is vital due to large upfront investments for coastal protection and the uncertainties associated with future sea-level rise. In particular, our view is that further investigation and investment is required for long-term engagement with coastal communities, including their businesses.

#### 6.3.2.4 What are the barriers preventing adaptation? (B2)

The barriers for adapting to coastal flooding are fairly similar to the barriers outlined for B1 discussed above, and for the coastal flooding and erosion risks described in Chapter 3 (Berry and Brown, 2021), Chapter 4 (Jaroszweski, Wood and Chapman, 2021) and Chapter 5 (Kovats and Brisley, 2021).

Barriers include short time frames of business planning; uncertainty in potential sea level rise at a given location over a given timescale; unclear responsibilities or lack of risk ownership; overreliance and trust in protection levels; and lack of confidence about ecosystem services. There is also a lack of research findings to inform businesses on the costs and benefits associated with business opportunities from innovative business adaptation in at-risk locations.

As is the case with other types of flooding, financial resources will not be available in the future to defend the entire coast of the UK, and so priorities as well as guiding principles are needed to allocate resources for coastal protection (Boston, Panda and Surminski, 2021). The National Trust Shifting Shores report (National Trust, 2015) recognises that the protection of coastal areas is ‘increasingly less plausible’ and supports adaptation strategies that move structures and assets out of risk zones and allow natural coastal dynamics and processes to take place. Flood protection may be appropriate in some cases, but this creates lock-in to protecting properties long-term. This can have threshold effects, additional carbon costs and could discourage more appropriate adaptive actions such as avoidance of flood risk in other areas. Our view on SMPs is that they have been welcome and vital in addressing key issues, like designating areas of No Active Intervention (NAI): where there is no planned investment in coastal defences or operations, regardless of whether or not an artificial defence has existed previously. However, from the evidence collated, there are several criticisms of the SMPs, including: a lack of clarity of how businesses, communities and development planners should use the shoreline management plans and lack of accessibility to the underpinning data and methods used. For North Norfolk, an SMP designation has arguably led to the emergence of coastal blight with house prices and investor confidence plummeting in several rural villages, such as Happisburgh, with 1400 households, and less than 50 small and medium sized enterprises (POST 2009). The risk of blight and the need for innovative financial solutions were highlighted by a parliamentary investigation of the Environment, Food and Rural Affairs Committee into ‘Coastal flooding and erosion, and adaptation to climate change’ (House of Commons, 2019).

Evidence is starting to emerge that the application of a coastal management policy of ‘managed realignment’ or ‘no active intervention’ with no implementation strategy creates significant negative

economic consequences for coastal stakeholders relating to loss of tourism income, assets and residential properties (Phillips *et al.*, 2018, Buser, 2020). A process of transition is occurring in the village of Fairbourne in Wales, whereby a new policy designation (in SMP2) recommends maintaining protection till 2025; managed realignment to 2055; and then no active intervention up to 2105 (Buser, 2020) – see Chapter 5 (Kovats and Brisley, 2021) for a case study on Fairbourne.

Some coastal communities, businesses and infrastructure may need to change in structure, focus, organisation, and location to become viable under future climates. CCC (2018) recommended that information on future coastal change needs to be communicated (unambiguously but with an appropriate recognition of uncertainties) to communities. The need for a ‘National Conversation’ about acceptable levels of risk and how future locations should change was the focus of a UK national conference on adaptation held in October 2020 (UK Climate Risk, 2020).

Policy transitions may also be required, from current strategic options to alternative options. This may create business opportunities in areas which find themselves able to access funding for development (after the policy change), and effective economic stagnation and loss in those areas which cannot access funding for development. The SMP-R should identify opportunities for coastal areas by considering the role of partnership funding and the policy designation within the SMPs (these can be ‘Hold The Line, No Active Intervention, Managed Realignment, or Advance the Line’). Further research is needed to clarify the implications of a transition from one policy option to another.

#### 6.3.2.5 Adaptation scores (B2)

**Table 6.10** Adaptation scores for risks to business locations and infrastructure from coastal change from erosion, flooding and extreme weather events

Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

### 6.3.3 Benefits of further adaptation action in the next five years (B2)

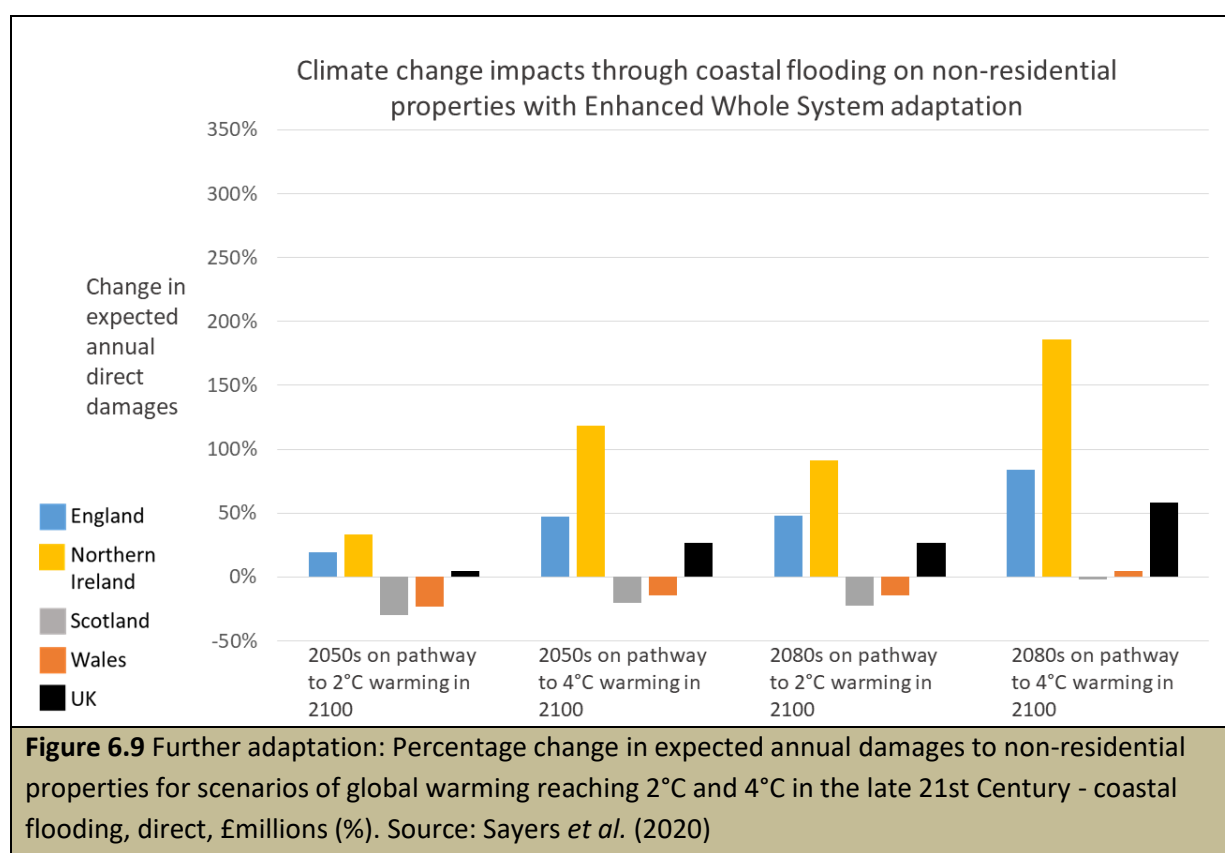
#### 6.3.3.1 Additional planned adaptation that would address the adaptation shortfall? (B2)

Adaptation actions in the next five years have the potential to enable business opportunities to be created from climate change impacts on the coast, and possibly to avoid further losses.

Opportunities exist for coastal businesses from the re-designation of management policy in coastal areas (e.g., from defended to undefended). Depending on the designation, the opportunity exists for businesses to bid for coastal partnership funding to redevelop the coastal area. There is also the

potential for business opportunities to emerge from habitat creation, or new approaches to construction to enable communities to ‘live with rising seas’. Coastal properties could also be purchased and repurposed to generate income, e.g., wind farms, temporary holiday lets (Coastal Partnership East, 2019). Overall there is a lack of research and evidence in this area. There is also a business opportunity for new designs/building structures, such as portable beach homes which can be lifted out of harm’s way, providing low impact low risk solutions for future sea-side tourism.

Sayers *et al.* (2020) report that if further adaptation measures are taken, in addition to what is currently planned (see Figure 6.8), then the UK-wide expected annual damages for non-residential properties will increase by 5% in 2050 and increase by 27% by 2080 compared to present day levels of expected damage in the 2°C warming scenario and increase by 27% by 2050 and 58% by 2080 in the 4°C warming scenario. It should be noted however that the Sayers report did not cover coastal erosion and was concluded before the publication of the National Flood and Coastal Erosion Risk Management Strategy (Environment Agency, 2020b) and the Flood and Coastal Erosion Risk Management Strategy Policy Statement (HM Government, 2020). Results are calculated under the Enhanced Whole System model, with results by country for both the 2°C and 4°C warming scenarios presented in Figure 6.9. As can be seen, additional adaptation would significantly decrease expected annual damages to non-residential properties in Scotland and Wales. It is important to note that adaptation solutions do not apply across the board and are context specific. For example, increased coastal protection may work in one community in response to sea level rise, but relocation may be more feasible for a different community.





Some other potential benefits of further adaptation in the next five years include increased transparency about protection levels and limits to avoid false sense of security; public engagement in developing future visions for coastal communities; or investments in community resilience.

According to the CCC coastal change report (CCC, 2018), one of the main factors that could aid implementation of more proactive, and cost-effective relocation of coastal properties and assets at risk (i.e., 'move the risk'), is a change in government policy, associated funding prioritisation and outcome measures. It should be noted that this report was published before the publication of the National Flood and Coastal Erosion Risk Management Strategy (Environment Agency, 2020b) and the Flood and Coastal Erosion Risk Management Strategy Policy Statement (HM Government, 2020). These changes could facilitate the ability to plan and implement the management approaches identified for each of the coastal areas around the UK, particularly those at high risk. More active business engagement with existing resources available for coastal development in 'at risk' areas would likely increase adaptation, for example through FCERM partnership funding and Grant-in-Aid support. New guidance was released on the Grant-in-Aid scheme in 2020 to help businesses identify what resources are available for adaptation and what additional funds would need to be secured.

Transparency around planned coastal designation changes (from defended to undefended) could support more active adaptation. Providing clearer communication and more transparency should help businesses to avoid a false sense of security and to allow them to plan for future climate risks. Given that the Shoreline Management Plans are non-statutory policy documents, they can only inform wider strategic planning. The Plans also do not consider the full scale of future climate change risks (e.g., high++ scenarios) and do not set out the more radical adaptation responses that could manage those risks.

The CO-designing the Assessment of Climate CHange costs (COACCH) research report (COACCH, 2019a) notes that the costs of adaptation vary significantly with the level of future climate change, the level of acceptable risk protection and the framework of analysis (protection versus economic efficiency). Recognising and working with uncertainty as part of integrated and sustainable policies requires an iterative and flexible approach that positions coastal change adaptation within a broader integrated coastal-zone management policy framework. For example, new coastal development visions should be fully aligned with climate futures. The COACCH Report, which also includes an analysis of adaptation in the UK, reinforces the message that the most appropriate response to sea-level rise for coastal areas is a combination of adaptation to deal with the inevitable rise and mitigation to limit the long-term rise to a manageable level (COACCH, 2019a)

Climate change forms part of a range of risks and uncertainties most industries routinely face. For example, seafood sector adaptations could include much closer science-industry collaboration and engaged research in the short term; and a move towards a more robust and strategic fisheries knowledge base in the medium term (Garrett *et al.*, 2015). More work is needed to identify business opportunities in high-risk coastal areas, including better understanding of funding resources, clearer communication and a realistic appraisal of the risks and opportunities for businesses at the coast.

More research is required to understand the costs and benefits of different adaptation responses to loss of coastal locations for businesses and infrastructure. Further analysis is required on how risk

will change in the future and how this should inform decisions on a national outcome and strategy for flood risk alleviation. The National Infrastructure Commission (NIC) proposed the adoption or exploration of national minimum standards of resilience (NIC, 2018) though as yet this has not been adopted by government.

Defra (2018) indicate that local businesses (potentially with assets at risk) are often an important source of partnership funding for larger schemes. This must be capitalised during stakeholder engagement. Moreover, critical business infrastructure like transport or ports, as well as industry critical business infrastructure such as industrial plants (i.e. chemical and petrochemical plants, oil refineries, gas processing plants) and factories (i.e., food processing facilities, pharmaceutical manufacturing), which are typically located on the coast or on tidal rivers / estuaries out of necessity for process feedstock import and finished product export can be given a level of protected status when it comes to government flood risk management, as suggested by ABP (2016). The Institute of Mechanical Engineers suggests that this infrastructure is vital to national economic prosperity and growth as well as local economies and communities (IMechE 2019).

Our view is that for some sectors and some parts of the UK, guidance on appropriate adaptation in the short term has been identified (e.g., fisheries in England and Scotland), however in other parts of the UK, more investigation is needed to identify pathways of action, for example in Northern Ireland. Since CCRA2, the policy environment has changed, creating new opportunities for businesses and creating more adaptation guidance and support in all four of the UK countries. In the longer term, actions relating to the institutional arrangements for adaptation could be considered. For example, governance of fisheries (of both regulated and non-regulated species) could be adapted in the short, medium and long term as there will likely be a need for flexible institutional arrangements to respond to climate change.

The finance sector can encourage adaptation by policyholders through incentivisation; Governments and insurers can play a key role by providing further financial incentives for adaptation; for instance, they can set policy premiums at a level that more closely reflects the risk to which individual properties are exposed. However, some elements of coastal change such as erosion are excluded from insurance. If adaptation measures are not implemented, the insurance that currently exists will become more expensive and less available. At present, flood insurance for businesses is being driven by private insurance companies, with low government scope or obligation to pay compensation (Sayers *et al.*, 2020). This issue merits further investigations given lack of consideration in current flooding evidence reports (Sayers *et al.*, 2020).

#### 6.3.3.2 Indicative costs and benefits of additional adaptation (B2)

The overall benefits of further investment in coastal flood management for commercial property – and the reduction in expected annual damages – are shown in Figure 6.8 and 6.9 The Sayers *et al.* (2020) study does not estimate the costs of these measures, and thus does not undertake a cost-benefit analysis. In general terms, the literature reports that coastal adaptation is an extremely cost-effective response, significantly reducing residual damage costs to very low levels (Hinkel *et al.*, 2014), however, in rural areas, such measures often have benefit-cost ratios lower than one. A new approach to investigating the wider dividends of adaptation and resilience interventions is

demonstrated by Roezer *et al.*, 2021 for the case of Felixstowe on the East Coast of England, where increased coastal protection from the new flood defences stimulated new investments in the property sector including the creation of new jobs and a boost to local businesses through increase in visitors, of which the local authority attributed around 50% to the new flood protection scheme. The assessment and retrospective evaluation of additional resilience dividends by the Coastal Partnership East (CPE), a group of local authorities, as part of the monitoring and valuation stage was done to support the business case for similar projects and future interventions. (Roezer *et al.*, 2021).

#### 6.3.3.3 Overall urgency scores (B2)

<b>Table 6.11</b> Urgency scores for risks to business locations and infrastructure from coastal change from erosion, flooding and extreme weather events				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency Score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Medium	Medium	Medium	Medium

Note: The evidence synthesized shows that current adaptation efforts will only partially manage the risk in future. There are benefits to action in the next five years, in particular, regarding additional support for critical business sites and infrastructure in coastal locations, as well as the role the finance sector can play in encouraging adaptation efforts by businesses. Further investigation of the opportunities to businesses from coastal adaptation would also be beneficial.

#### 6.3.4 Looking ahead (B2)

There are a range of areas that require urgent attention to help manage coastal change across the UK: Data on exposure to erosion and storm damage remains patchy for much of the UK coast, there is no centralised evidence base that can be easily accessed (along the lines of the Environment Agency's flood risk maps). In addition, data access is not uniform across the UK, clear differences exist between England, Wales, Scotland and Northern Ireland. New evidence, such as Sayers *et al.* (2020) is informative but does not include coastal erosion risks or cost-benefit analyses. Going forward, coastal flooding and coastal erosion should be assessed jointly and with a specific focus on direct and indirect implications for businesses. For CCRA4, a more complete, detailed assessment of coastal risk and vulnerability across all four nations would be a useful starting point.

### 6.4 Risks to businesses from water scarcity (B3)

The risks that water scarcity pose to businesses in the UK are scored as 'further investigation' due to significant gaps in analysis. Given the importance of water for a wide range of sectors and business

functions any disruption to supply and accessibility can cause significant disruption. Water is used by businesses for cooling and heating, washing products, dissolving chemicals, suppressing dust and also as a direct input to products. Water is also being used by people working in businesses for drinking, washing and sanitary purposes, similar to domestic users. Water-intense manufacturing sub-sectors such as chemicals and chemical products, basic metals, paper and paper products, beverages and food products are more vulnerable to water scarcity. In terms of highest overall use, the manufacturing sector is the biggest abstractor, being responsible for between approximately 45% and 55% of direct abstractions. Other relatively large abstractors include mining and quarrying, as well as arts, entertainment and recreation, and other goods and services. The degree to which businesses will change their water requirements due to socioeconomic circumstances is highly uncertain but potentially a significant driver of risk. If not well managed, risk of water shortage is projected to become material in investment and employment for water-intense sectors. Risks to public water supply in general are covered in Chapter 4 (Jaroszowski, Wood and Chapman, 2021), and international water risks to businesses are covered in Chapter 7 (Challinor and Benton, 2021).

#### 6.4.1 Current and future level of risk (B3)

According to UNEP's CEO Water Mandate, water scarcity becomes a concern for businesses if they are unable "to access adequate water supplies or services to effectively manage a company's operations". This can be caused by drought or long-term water scarcity (i.e., insufficient and/or unreliable access to water); flooding (causing damage to infrastructure and/or disruptions in supply); or pollution, to the extent that such water is rendered unfit for operational use. This is most often a problem for companies with water-intensive operations in water-scarce regions. In addition, there are regulatory risks when policymakers and/or water managers change laws, regulations or management practices in ways that alter companies' access to water, increase the costs of operation, or otherwise make corporate water use and management more challenging. Businesses are also exposed to reputational risks if business water use are deemed to be inefficient or harmful to watersheds, ecosystems, and/or communities (UNEP, 2010). Without sufficient water, production in many businesses would have to be reduced or stopped (CCC, 2015). Businesses obtain water either directly through the public water supply system, or through direct abstraction from natural sources such as rivers and groundwater supplies. Water-intense manufacturing sub-sectors such as chemicals and chemical products, basic metals, paper and paper products, beverages and food products are more vulnerable to water scarcity (CCC, 2014).

Across CCRA3 water use by different sectors is covered in different sections of this report: Chapter 3 (Berry and Brown, 2021) reports on water demand and use from the natural environment, agriculture and forestry; Chapter 4 (Jaroszowski, Wood and Chapman, 2021) by critical infrastructure sectors, including assessing the risks to public water supply and water for direct abstraction by infrastructure providers; and Chapter 5 (Kovats and Brisley, 2021) looks at the risks from water supply interruptions on households. This section focusses on risks to businesses that are not covered in Chapters 3 (Berry and Brown, 2021), Chapter 4 (Jaroszowski, Wood and Chapman, 2021) and Chapter 5 (Kovats and Brisley, 2021). Specifically, this section considers how water scarcity risk may affect different site locations for any type of business.

## 6.4.1.1 Current risk (B3)

## 6.4.1.1.1 Current risk - UK-wide

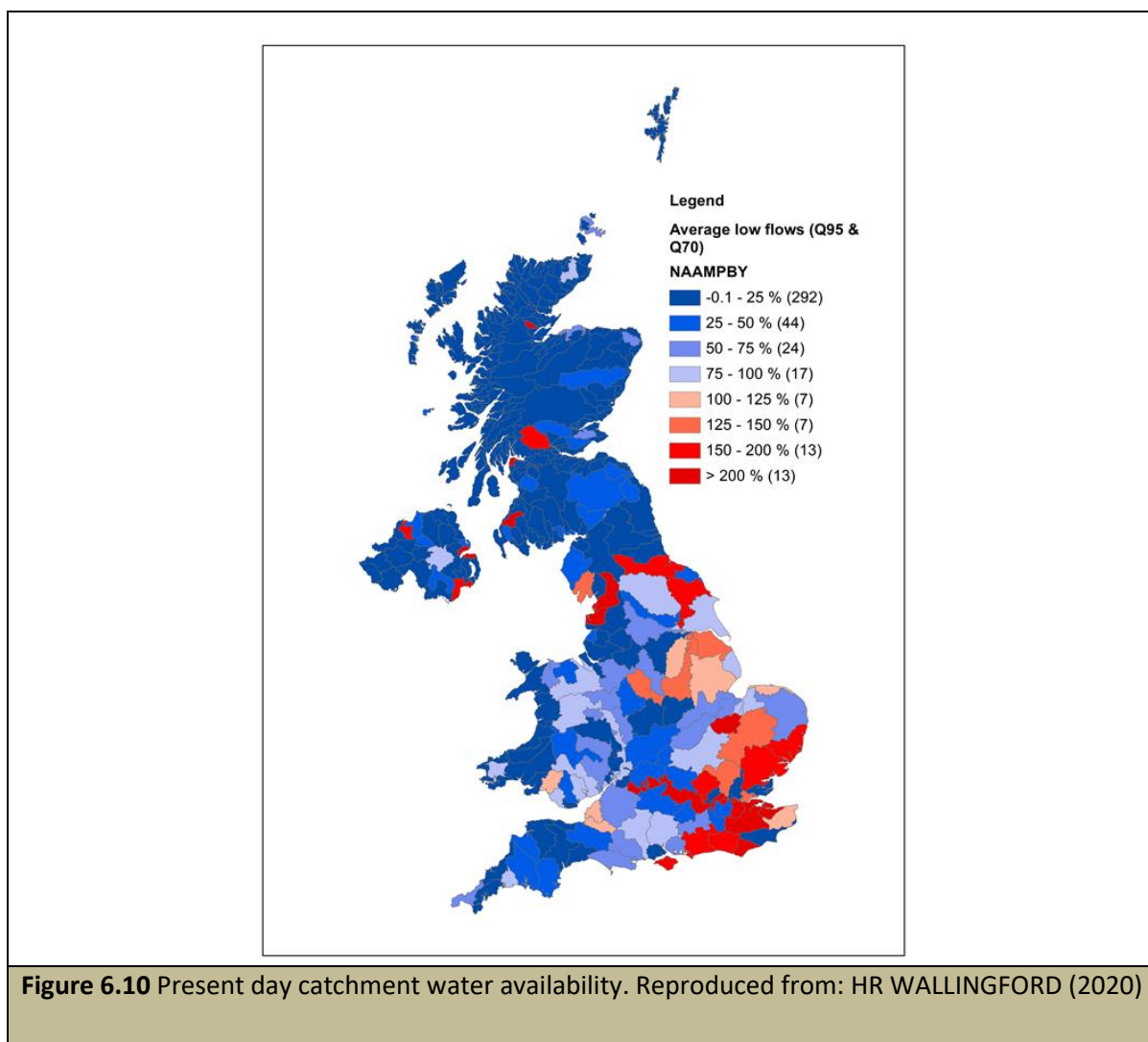
HR Wallingford's recent report (HR WALLINGFORD 2020) offers insights into current and future water scarcity risks for businesses by analysing risks for the public water supply, and by projecting changes in catchment water availability that may impact businesses that rely on their own abstraction licenses rather than the public water supply. An important aspect is non-household water demand, which, as shown in Table 6.12, currently accounts for around 20% of demand in each UK country, lower than household demand and water leakage (HR WALLINGFORD, 2020).

**Table 6.12** Main components of baseline (~2019/20) supply-demand balance, deployable output and demand in the four countries of the UK. Source: HR WALLINGFORD (2020).

Country	Supply-demand balance (MI/d)	Deployable output (MI/d)	Water Available for Use	Demand MI/d (% of total demand)					Target Headroom
				Household	Non-household	Leakage	Other	Total demand	
England	400	16,250	15,150	7,790 (56%)	2,830 (20%)	2,940 (21%)	320 (2%)	13,880	870
Wales	80	1,060	1,010	460 (55%)	180 (21%)	170 (20%)	20 (2%)	840	90
Scotland	300	2,260	2,340	830 (44%)	410 (22%)	590 (31%)	60 (3%)	1,890	150
Northern Ireland	170	840	770	290 (51%)	110 (19%)	160 (28%)	20 (4%)	570	30

Figures in Table 6.12 are rounded to the nearest 10 MI/d (million litres per day) and are informed by the latest water company resource plans. Factors such as target headroom, sustainability and other reductions in deployable output are not recorded in this table, so deployable output minus demand does not equal the supply-demand balance. 'Other' demand includes more ad-hoc water demand, such as that required for firefighting.

For the public water supply, the study finds that all four countries in the UK currently maintain a supply-demand balance surplus. However, at a water resource zone scale, some deficits already exist in water companies' draft baseline plans available at the time of the study. For abstraction, the study finds that the majority of UK catchments are not currently using 100% of the available resource of water at average low flow conditions, i.e., there is a surplus of water available for human uses, though there could be deficits for individual water bodies within a catchment. There are 40 catchments where abstraction demand is already in excess of the available resource in average low flow conditions. These catchments are mostly located in the east and south of the UK, although there are a small number of catchments in Scotland, Northern Ireland and the north-west of England. For businesses specifically, we assess that this evidence suggests a low magnitude risk (medium confidence) for the present day. This is discussed further in Chapter 5 (Kovats and Brisley, 2021).



However, stress on the system during heat waves and accidental disruption to supply has an impact on some sectors, especially water intense industries such as those producing chemical products, paper products and food and drink (Scottish Government, 2019). Moreover, as stated by HR Wallingford (2020) changes in product design in one sector do drive up water demand in another, and this can lead to increase water demand or a shift in the location of demand. An example is a shift from plastic packaging to paper-based packaging, which may see a decrease in water demand in the chemicals manufacturing sector and an increase in demand in the paper manufacturing sector.

#### 6.4.1.1.2 Current risk - England (B3)

In England, around 1 billion litres of water a day are used by industry, power generation, and farming (Environment Agency, 2020a). At present, there is a national surplus of around 400MI/day in the public water supply in England (HR WALLINGFORD, 2020) with no immediate restrictions for business users. As per MOSL (2020) business water usage is highly concentrated: just 200,000 businesses use 90% of the supplied water to businesses in England. Businesses also account for around 9% of direct abstractions from freshwater sources in England (CCC 2019a), with overall abstraction levels currently higher than in 2013, despite an 8% drop from 2014 to 2017 (CCC 2019a).

These changes could be the result of adjustments in production levels or other trends rather than improvements in water efficiency. It is not known how many abstraction licences held by businesses have been adjusted as part of abstraction reform to date. Vivid Economics *et al.* (2013) in a study for Defra estimated that in England £165m in revenue, and £96m in profit was lost by firms and sites in the second quarter of 2012 during the drought early in the year.

#### 6.4.1.1.3 Current risk - Scotland (B3)

At present there is a slight deficit of around 20 MI/day in the public water supply in Scotland (HR WALLINGFORD, 2020). There has been a sustained decrease in the annual average volume of non-domestic water used per day between 2008/09 (466 MI/d) and 2016/17 (394 MI/d) (CCC, 2019b) though as for England it cannot currently be determined what is driving this drop. Data is not currently available on direct abstractions by businesses in Scotland. Business impacts from drought conditions have been reported for the drinks sectors, with whisky producers in Scotland losing output due to drought conditions in 2019, with one distillery reporting the loss of one production month (The Drinks Business, 2019).

#### 6.4.1.1.4 Current risk - Wales and Northern Ireland (B3)

Wales and Northern Ireland both have surpluses in the public water supply of 80 and 170 ml/day respectively, but water abstraction levels for business use remain unclear.

#### 6.4.1.2 Future risk (B3)

##### 6.4.1.2.1 Future risk - UK-wide

The future risks to businesses specifically from water scarcity are potentially very large but also unquantifiable. A Water UK report (Water UK, 2016) states that “*water restrictions could have a range of consequences on businesses and public sector bodies connected to the public water supply, and on sectors wholly or partially reliant on private abstraction sources.*” These risks are not just about loss of production, but also health and safety risks to employees if water supplies at site premises are cut off, and this is a risk for all businesses not just intensive water users (Environment Agency, 2016). Power *et al.* (2020) report that in a severe drought situation, where private supplies became unavailable or were restricted, the majority of abstracting firms would attempt to switch to Private Water Supplies where and for as long as such supplies were available. The authors also found that if private back-up supplies were to be unavailable, most firms did not have a contingency plan in place to allow them to continue to produce with a reduced private water supply, which would imply a fall in production at such locations and for the period when private water was unavailable. Estimates of the economic costs for a number of hypothetical drought scenarios differing in duration, severity and in decade of occurrence ranged from £261m in a one-year severe drought in 2010s to £43,488m in a three-year extreme drought in 2050s. (Power *et al.* 2020)

The National Infrastructure Commission (NIC) compared the short-term emergency costs of providing water during a drought, weighted by their probability of occurrence in the 2020 to 2050 period, with the whole-life costs of building long-term resilience to an equivalent event. The results

show that at a national level, the cost of responding to a drought emergency are higher than those of building long-term resilience to the same event (NIC 2018).

HR Wallingford (2020) project changes in water resources on pathways to global warming of approximately 2°C and 4°C in the late 21<sup>st</sup> Century<sup>9</sup>. These warming pathways were termed “2°C world” and “4°C world” respectively in that study, and that naming convention is used here.

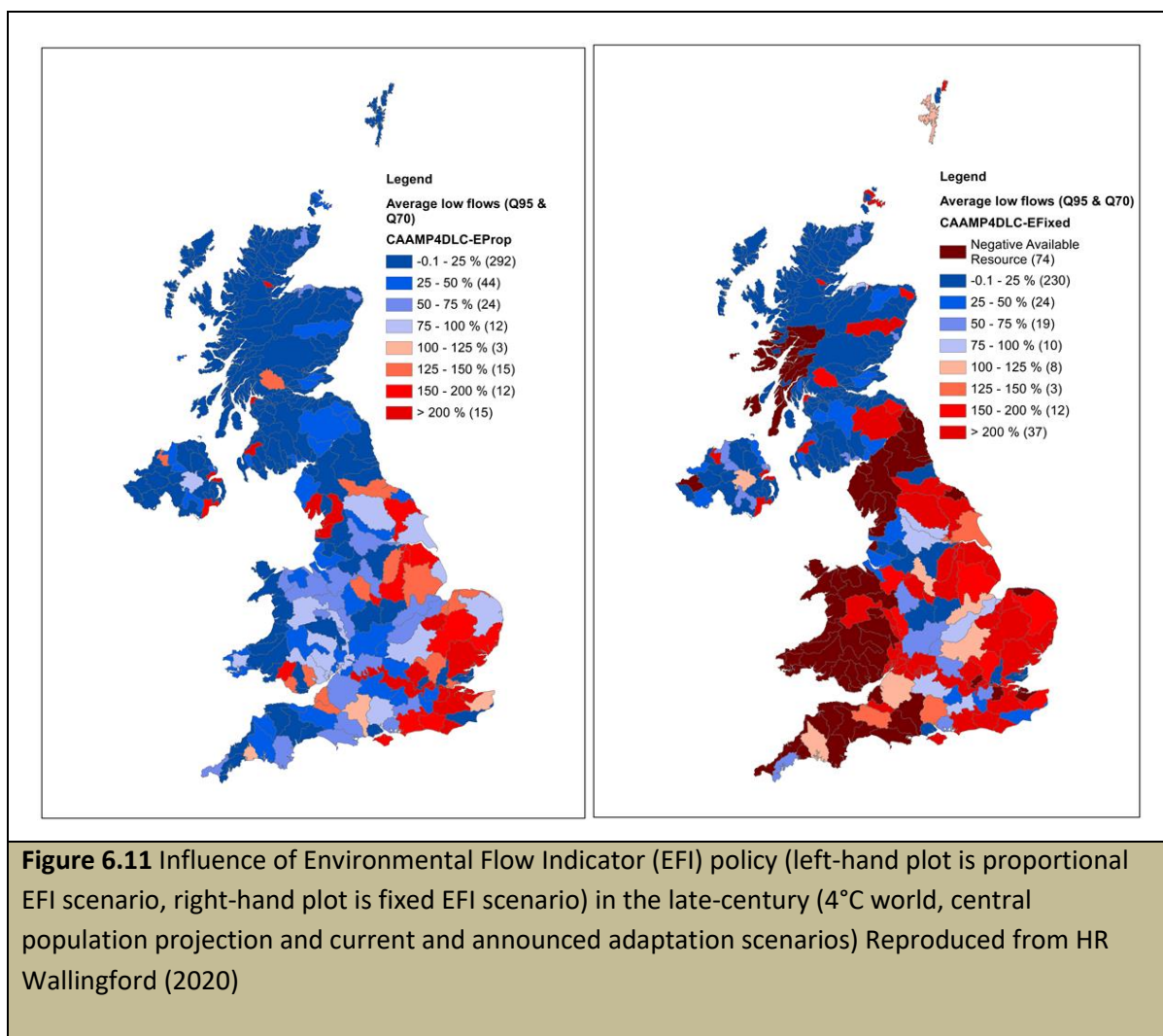
The results for all sectors from HR Wallingford (2020) suggest projected changes in river flows at times of low flows (Q95) across the UK are of the order of 0-20% reduction by the mid-century in a 2°C world, everywhere except the western highlands in Scotland (where flows increase). In a 4°C world, this reduction increases (up to 30% flow reduction) in some areas, such as the Severn and Tweed river basins. Projected changes in river flows at Q95 across the UK are of the order of 0-50% reduction by the late century with approximately 4°C global warming. Projected changes in river flow will influence the naturally available resource at Q95 that is available for both large and small abstractors (i.e., those with and without abstraction licences).

When the demands of abstractors are taken into account, catchments at risk of negative available resource i.e., not being able to meet the fixed volume environmental flow requirement before any other abstraction from people, tend to be along the west coast of Great Britain, where the reductions in low flows tend to be greatest. The HR Wallingford study finds that the most significant factor for all the sectors results is the policy for managing environmental flows, while the difference between the 2°C and 4°C worlds for these results is small. It models a scenario where the policy is to keep the environmental flows fixed at the same absolute volume that they are today. Under this scenario, many catchments across England, Wales, some in Scotland and one in Northern Ireland are unable to meet their environmental flow requirements without the addition of discharges to the river network. In the mid-century (4°C world, central population projection and current and announced adaptation scenarios) 22 catchments across the UK, are projected to have negative resource availability i.e. the current absolute volume of environmental flow could not be met. In the late-century (4°C world, central population projection and current and announced adaptation scenarios) 74 catchments across the UK, including some in the south west and far north of England, are projected to have negative resource availability i.e., the current absolute volume of environmental flow could not be met. This is shown in Figure 6.11.

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<sup>9</sup> The HR Wallingford (2020) method defined the 2°C and 4°C pathways as the global warming levels (GWLs) reached late century (2070-2099) at the 50<sup>th</sup> percentiles of the UKCP18 probabilistic projections with the RCP2.6 and RCP8.5: 1.8°C and 4.2°C respectively. The former is near the centre of the lower CCRA3 scenario, and the latter is on the upper bound of the CCRA3 higher scenario (see Chapter 2: Watkiss and Betts, 2021). Late-century regional climate states were taken from the UKCP18 perturbed-parameter ensemble (PPE) of global 60km projections at those GWLs. Mid-century climate states were taken from the 60km PPE at the GWLs reached with RCP2.6 and RCP85 50<sup>th</sup> percentiles in 2040-2069. See HR Wallingford (2020) for details.





#### 6.4.1.2.2 Future risk - England (B3)

For England the Environment Agency has estimated the water usage by 2050 in different sectors and regions. For industry the greatest increase is expected in the West and South-East. The EA's modelling assumes that around 700 million litres per day of water that comes from unsustainable abstractions will need to be replaced by other means between 2025 and 2050. (Environment Agency 2020a). Vivid Economics *et al.* (2013) estimated the impact that an extended drought scenario would have on key sectors based on recent drought experiences. By assuming that management actions taken during the 2011/12 drought would have been applied for the extended period, the study estimated that cumulative "first round" turnover losses would have amounted to just under £2.9 billion over the two-year period, equivalent to 6% of the total turnover under business as usual; and cumulative first round profit losses amount to just under £1.46 billion over the two year period, equivalent to 7 per cent of the total profit under business as usual. (Vivid Economics *et al.* 2013).

HR WALLINGFORD (2020) project that England's Supply-Demand Balance in the mid-century could be between 40 MI/d and -2,700 MI/d based on their analysis of public water supplies and depending on the extent of climate change and population growth and assuming no additional adaptation to

today. The Supply-Demand Balance for a central population projection is between -1,100 to -1,330 MI/d for 2°C and 4°C worlds respectively. In the late-century England's Supply-Demand Balance could be between 40 MI/d and -5,230 MI/d depending on the extent of climate change and population growth and assuming no additional adaptation to today. The Supply-Demand Balance for medium population projections is between -1,660 MI/d and -3,180 MI/d for 2°C and 4°C worlds respectively. The study finds that if the assumed policy is to keep the environmental flows fixed at the same absolute volume that they are today, many of the catchments across England are unable to meet their environmental flow requirements without the addition of discharges to the river network (HR WALLINGFORD 2020).

#### 6.4.1.1.3 Future risk - Northern Ireland (B3)

The results for public water supplies from HR Wallingford (2020) project that Northern Ireland's Supply-Demand Balance in the mid-century could be between 170 MI/d and 10 MI/d depending on the extent of climate change and population growth and assuming no additional adaptation to today. The Supply-Demand Balance for the central population projection is between 120 and 100 MI/d for 2°C and 4°C worlds respectively.

In the late-century Northern Ireland's Supply-Demand Balance could be between 162 MI/d and -47 MI/d depending on the extent of climate change and population growth and assuming no additional adaptation to today. The Supply-Demand Balance for the central population projection is between 120 MI/d and 80 MI/d for 2°C and 4°C worlds respectively. Where the policy is to keep the environmental flows fixed at the same absolute volume that they are today, one of the catchments in Northern Ireland is unable to meet its environmental flow requirements without the addition of discharges to the river network (HR WALLINGFORD 2020).

#### 6.4.1.2.4 Future risk - Scotland (B3)

The results for public water supply from HR Wallingford (2020) project that Scotland's Supply-Demand Balance in the mid-century could be between 450 MI/d and 0 MI/d depending on the extent of climate change and population growth and assuming no additional adaptation to today. The Supply-Demand Balance for the central population projection is between 290 and 260 MI/d for 2°C and 4°C worlds respectively.

In the late-century Scotland's Supply-Demand Balance could be between 440 MI/d and -170 MI/d depending on the extent of climate change and population growth and assuming no additional adaptation to today. The Supply-Demand Balance for the central population projection is between 280 MI/d and 190 MI/d for 2°C and 4°C worlds respectively.

Where the assumed policy is to keep the environmental flows fixed at the same absolute volume that they are today, some of the catchments in Scotland are unable to meet their environmental flow requirements without the addition of discharges to the river network (HR WALLINGFORD 2020).

#### 6.4.1.2.5 Future risk - Wales (B3)

The results for public water supply from HR Wallingford (2020) project that Wales' Supply-Demand Balance in the mid-century could be between 110 MI/d and -60 MI/d depending on the extent of climate change and population growth and assuming no additional adaptation to today. The Supply-Demand Balance for the central population projection is between 60 and 40 MI/d for 2°C and 4°C worlds respectively.

In the late-century Wales' Supply-Demand Balance could be between 110 MI/d and -130 MI/d depending on the extent of climate change and population growth and assuming no additional adaptation to today. The Supply-Demand Balance for the central population projection is between 60 MI/d and -10 MI/d for 2°C and 4°C worlds respectively.

The results for all sectors from HR Wallingford (2020) suggest projected changes in river flows at Q95 (low flows) across the UK are of the order of 0-20% reduction by the mid-century in a 2°C world everywhere. In a 4°C world, this reduction increases (up to 30% flow reduction) in some areas, such as in Wales, impacting the naturally available resource at Q95 for both large and small abstractors (i.e. those with and without abstraction licences). Catchments at risk of negative available resource i.e. not being able to meet the fixed volume environmental flow requirement tend to be along the west coast of Great Britain, where the reductions in low flows tend to be greatest. In the late-century (4°C world, central population projection and current and announced adaptation scenarios) 74 catchments across the UK, many in Wales, are projected to have negative resource availability i.e. the current absolute volume of environmental flow could not be met.

#### 6.4.1.3 Lock-in and thresholds (B3)

##### 6.4.1.3.1 Are there lock-in risks? (B3)

There is limited evidence about the extent of lock-in in terms of water dependency. Choice of business processes in terms of reliance on highly water-intensive production processes may lock-in a business and pose risks especially for those with direct abstraction licences, because of the emerging deficits, and thus the likelihood of higher water charges or potential disruptions. WRAP (2011) published an analysis of freshwater availability and use in England and Wales, which suggested that, using the Standard Industrial Classification (SIC) 2007, the manufacturing sector was the biggest abstractor in 2006, being responsible for between approximately 45% and 55% of direct abstractions. At a regional level, over 65% of these abstractions were in the north-west of England or in Wales. Other relatively large abstractors included mining and quarrying, as well as arts, entertainment and recreation, and other goods and services. Certain manufacturing sub-sectors accounted for more abstractions than others. These included the manufacturing of chemicals and chemical products, basic metals, paper and paper products, beverages, food products and coke and refined petroleum products. An example is the British brewing sector: valued at over £20 billion, this highly water-intensive industry had to invest significantly in water efficiency programmes, such as lowering the water use ratio needed to make beer from 10:1 to around 4:1 (Raconteur, 2018).

#### 6.4.1.3.2 Are there potential thresholds? (B3)

At the national scale, there do appear to be thresholds as the UK, and England in particular, is projected to move into a supply-demand balance deficit by the 2050s, and the timing of this, and the subsequent increase in the deficit, will vary between 2°C and 4°C worlds. These would have implications for business water use.

There are also potential thresholds associated with levels of extreme events, though it is difficult to predict when particular thresholds may be crossed, that would lead to a sudden increase in risk to businesses from increased water scarcity. Water drought frameworks and drought plans can provide these thresholds as drought levels are somewhat predictable and would trigger restrictions and possible risks to businesses (those deemed non-essential use). In terms of extremes, current water company plans have typically focused on a 1 in 100-year event, taking account of climate change (although some companies have started applying a 1 in 200 chance of occurrence, as required by the latest water resources planning guidelines). The National Framework asks regional groups to plan for 1 in 500. Other recent analysis (Water UK, 2016) has looked at high climate futures, which include scenarios of drier summers, wetter winters and higher variability. But no single threshold has been identified to date. There also may be policy thresholds, as HR WALLINGFORD (2020) highlight. Thresholds for drought response are currently managed within companies. Each water company has its criteria for deciding that it's reached a certain drought level. The different UK environmental regulators also have different drought levels. And at those levels, different responses are put in place, which eventually include restrictions on non-essential use. In the future, whilst the thresholds may not change the frequency with which they are breached will.

#### 6.4.1.4 Cross-cutting risks and inter-dependencies (B3)

The coincidence of hot weather with drought can potentially exacerbate risks and severe water scarcity could have impacts on people, who would then perhaps not be able to work, and potential for reduced demand for products and services. Further analysis of these interdependencies would be required to assess risk levels.

Some businesses have considered where water scarcity will affect wider supply chains and not just site locations. Marks & Spencer's (M&S) completed a top level assessment which confirmed that more than 90% of its water use as a business is within its supply chains. This is likely to be fairly common for most companies with agricultural supply chains and suggests that influencing and engaging suppliers and other stakeholders in collective action in water risk hotspot areas where a business sources and operates will be the key route to addressing overall water risk for most retail businesses. Moreover, HR Wallingford (2020) suggest that in a scenario where which self-sufficiency, sustainability and increased demand for 'home-grown' products is valued, in the absence of other adaptations, there could be increased water demand across a variety of industries. There are also cases of opportunities for business arising from climate change risks. An example of this is seen in the Viticulture sector in the UK (see opportunity B7) where in 2018 some producers became concerned about drought and started using irrigation for their plants (CREW, 2020).

## 6.4.1.5 Implications of Net Zero (B3)

Rising temperatures will increase water demand, and water supply and use involves energy use and carbon emissions, although in the long term this energy is expected to be zero carbon. The water industry was the first industrial sector in the UK and one of the first major sectors to commit to a carbon zero future by 2030, as established in the Net Zero 2030 route map that was published in 2020. The goal forms part of the industry's Public Interest Commitment (PIC) released in 2019 (See Chapter 5: Kovats and Brisley, 2021). More efficient water use can deliver energy and carbon savings for businesses as well as for the water sector. Indeed, for many companies their Net Zero commitment could be a greater incentive to reduce water use than saving water per se. There may be some businesses that might implement water re-use systems to increase efficiency, and this would be more energy intensive (Chhipi-Shrestha *et al.*, 2018). However, this is a relatively small proportion of the businesses.

At the same time, some low carbon technologies are also potentially water intensive (Chapter 4: Jaroszowski, 2021), including hydrogen generation and carbon capture and storage; and this could create additional competition for water.

## 6.4.1.5 Magnitude scores (B3)

<b>Table 6.13</b> Magnitude scores for risks to businesses from water scarcity					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>England</b>	Low  (Medium confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	High  (Low confidence)
<b>Northern Ireland</b>	Low  (Medium confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	High  (Low confidence)
<b>Scotland</b>	Low  (Medium confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	High  (Low confidence)
<b>Wales</b>	Low  (Medium confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	High  (Low confidence)

The magnitude scoring follows the evidence above and our expert judgement. Currently magnitude is low across the UK. For the public water supply, the HR Wallingford study (2020) finds that all four countries in the UK currently maintain a supply-demand balance surplus, though there may be some more acute problems at the Water Resource Zone level. Similarly, for abstraction, the study finds that the majority of UK catchments are not currently using 100% of the available resource of water at average low flow conditions, though there are some where abstraction demand is already in excess of the available resource and there may be issues for individual water bodies within catchments. For business specifically, our expert judgement of this and the available evidence is that the annual economic impact is currently estimated to be less than £10million of damage in England and less than £1 million of damage or foregone opportunities in Wales, Northern Ireland and Scotland. These risk levels could change to medium and high if not managed. The degree to which businesses will change their water requirements due to socioeconomic circumstances is highly uncertain but potentially a significant driver of risk. If not well managed, risk of water shortage is projected to become material in investment and employment for water-intense sectors.

#### 6.4.2 Extent to which the current adaptation will manage the risk or opportunity (B3)

##### 6.4.2.1 Effects of current adaptation policy and commitments on current and future risks (B3)

###### 6.4.2.1.1 UK-wide

Chapter 4 (Jaroszweski, Wood and Chapman, 2021) sets out the current government-led adaptation plans in place for public water supply, and the plans in place and the adaptation deficit in terms of the supply-demand balance deficit. Chapter 5 (Kovats and Brisley, 2021) considers this risk in relation to household demand. The policy framework includes the requirement for water companies to produce a Water Resources Management Plan (WRMP), which cover a 25-year planning period, and investment plans over the period (note that the HR WALLINGFORD projections above used the draft water company baseline plans available at the time of the study for its current and announced adaptation scenario).

###### 6.4.2.1.2 England

The 25 Year Environment Plan (25 YEP) (HM Government, 2018) sets out the goal of boosting the long-term resilience of homes, businesses and infrastructure to climate change. This includes a goal to reduce the risk of drought and it sets a target of ensuring interruptions to water supplies are minimised during prolonged dry weather and drought. It is also noted that the 25YEP has a goal of making sure that all policies, programmes and investment decisions take into account the possible extent of climate change this century, which would apply to water investment decisions. However, there is very little specific information in the 25YEP on exactly what these targets involve (what is the metric of resilience, and what level to minimise to?), and what actions will be taken to achieve them. There is also a resilience objective recommended by the National Infrastructure Commission (NIC, 2018), which is for increasing the current levels of resilience (for droughts). The new national framework for water asks companies to increase resilience by planning for a 1 in 500-year drought

rather than 1 in 100. The Commission estimated that this would require additional capacity of 4,000MI/day by 2050, considering a medium emissions scenario. Greater levels of adaptation might be required under a more severe climate scenario. Defra's Environment Bill at the time of writing proposes a water demand target that would include business use of public water supplies as well as household use and leakage (Defra consultation, 2019).

The business retail market accounts for nearly a third of all water delivered to customers in England (Water Services Regulation Authority - Ofwat and Environment Agency, 2020). This 30% of public water supply consumed outside of the home is called 'non-household use' (NHH). NHH is not as well understood as domestic use in England and reducing NHH consumption had largely been left to the new retail market rather than addressed through any government or regulatory interventions. This failure of the market to sufficiently drive water efficiency was recognised in a recent Ofwat-Environment Agency joint letter, which outlines steps industry must take to improve levels of water efficiency. These steps include increased collaboration between wholesale and retailers through Water Resource Management Plans (WRMPs), improving meter reading and data quality of water consumption data, and increased coordination during unplanned events and incidents (Ofwat and Environment Agency, 2020). In March 2020 the Environment Agency published the national framework for water resources which sets out the strategic direction for long term regional water resources planning in England. Five regional water resources groups, comprised of water companies serving each area, will be producing coordinated cross-sector plans to manage demand and increase supply, and to realise opportunities stemming from collaborative working.

### 6.4.2.1.3 Northern Ireland

The Water Resource and Supply Resilience Plan published by NI Water runs several assessments of water scarcity risks. Although the report shows that for most of Northern Ireland there is expected to be sufficient water over the next 25 years, it indicates possible shortages at the end of that period unless demand management and other adaptation action is implemented. It suggests that without adaptation action there is "increased likelihood of water use restrictions being applied with impacts on households and business" (Northern Ireland Water, 2020). Resource Efficiency capital grants are provided to Invest Northern Ireland client companies to invest in resource efficient technologies. Grants of up to £40k are available to help with the purchase of new equipment that will reduce the consumption of water, waste and raw materials. The rate of support is based on company size (a maximum of 10% of total eligible project costs for large businesses, 20% for medium and 30% for small and micro) (Invest Northern Ireland, 2020).

### 6.4.2.1.4 Scotland

In Scotland, SEPA's Water Scarcity Plan (SEPA, 2015) includes a hierarchy of action in response to dry weather and encourage business contingency planning. Again though, it is not yet known how this is translating into action on the ground. Scottish Water also undertook an update of its strategic Climate Change Risk Assessment (CCRA) for assets, to refine the understanding of future climate-related risks and to identify knowledge gaps for further research. The Second Scottish Climate Change Adaptation Programme 2019-2024 (Scottish Government, 2019) includes several measures for water scarcity management and examples from the Scottish Whiskey sector.

#### 6.4.2.1.5 Wales

In addition to the broad actions to support businesses set out in 'Prosperity for All: A Climate Conscious Wales (2019)' (see risk B1), the plan sets out current policy relating to water supply as a whole. It states that mitigating the effects of climate change on water resources in Wales is deeply embedded in the development of Welsh Government policy, the regulation of the industry and planning and investing for the future. The Water Strategy for Wales (Welsh Government, 2015) sets out Welsh Government's vision and approach to ensuring a resilient, and affordable water supply and environment over the next 25 years. The strategy, which recognises the challenges that climate change brings, sets Water for Nature, People and Business as one of its 6 key themes.

Water Resource Management Plans in Wales are produced by water companies, and factor in climate risk to water demand, supply, output, river flows and account for population growth. They cover a twenty-five-year period and are required to take into account climate change projections, population growth and new developments. It is important to note that they currently utilise UKCP09 data (Dwr Cymru Welsh Water, 2019).

#### 6.4.2.2 Effects of non-governmental adaptation (B3)

In general, businesses can take measures to reduce the risks of water scarcity by taking measures to improve water efficiency and having contingency plans in place to deal with water scarcity. Businesses will take action when the (private) benefits of doing so outweigh the costs. However, in our view there are a number of barriers stemming from high uncertainty on climate risks and adaptation costs and benefits, market prices and externalities, inertia and procrastination, and policy failures which prevent the private sector from taking the appropriate level of adaptation. The Government can therefore play a key role in providing a regulatory framework which incentivises the uptake of water efficiency measures (e.g. mandatory efficiency labelling of water using products here as well as metering) thus creating the right incentives for water companies to provide and for businesses to adopt measures to reduce water demand.

In terms of end-user responses by businesses, the level of adaptation overall is unknown (for all four UK countries) – but there are promising signs of progress. There are some plans in place to reduce water use by businesses through the implementation of abstraction reform, the water retail market and company initiatives and targets.

There is also some information on water efficiency, which is a potentially low or no-regret adaptation response. Following a letter from Ofwat and the Environment Agency (2020) to water retailers and wholesalers in England and Wales, the Retailer Wholesaler Group has developed an action plan setting out how they will work together and with regulators to deliver greater water efficiency to businesses (MOSL, 2020).

For example, the textile industry currently has a large water-to-dye ratio footprint. Some businesses are experimenting in reducing this from 30 to 1 to 10 to 1 to make the water usage more efficient. Some businesses are also exploring near-waterless dyeing (Guardian, 2013). Additionally, in their 2018 European Report, CDP stated that 92% of businesses reporting on water had some sort of



target or goals in place within their operations, up from 61% the year before. Members of the Food and Drink Federation (FDF) have committed to contribute to an industry-wide target: to reduce water use outside of that embedded in products by 20% by 2020 relative to a 2007 baseline. Reporting members of the FDF had gone beyond this and reduced their water use by 39% in 2017 relative to the 2007 baseline. Data suggest that this was due to improvements in efficiency as water intensity had decreased from 2.5m<sup>3</sup> per tonne of product in 2007 to 1.5m<sup>3</sup> in 2017. Some further examples of actions underway are included in Box 6.2.

#### Box 6.2 Examples of business actions to reduce water use

##### M&S (WWF and M&S, 2017)

- Water stewardship is embedded into M&S's Food Sustainability scorecard programme and Clothing and Home Eco Factory and dye house standards. For example, The Foods Sustainability Scorecard programme has helped reduce water usage for direct suppliers by 8.5million m<sup>3</sup> (2014/15 vs 2013/14). It also encourages suppliers to embed the water stewardship approach within their supply chains.
- Suppliers have been supported with face-to-face training and webinars on addressing water risks.
- All produce growers are working towards agricultural sustainability standards which cover good water management.
- Water Stewardship Framework developed to trial with food producers.
- M&S is involved in collective action initiatives and water stewardship programmes in Kenya, South Africa, Spain and Peru.
- There is a long-term strategy partnership with WWF which includes work on fresh water.
- All key supply chains in food and clothing and home have been mapped and analysed using the WWF Water Risk Tool.
- Water risk in commodities is being addressed by working with certification schemes (e.g., Better Cotton Initiative) and through direct projects with growers.
- As a business, M&S is on track to meet targets to reduce direct water use in stores and offices by 35% by 2020.
- M&S has comprehensive measurement systems in place and targets to reduce water use across their estate/stores. During 2015/16, their UK and ROI store, office and warehouse water use was down by 31% at 46 litres per 100 sq. ft (2006/07: 67 litres per sq. ft).

##### Supermarkets (NERC, 2018):

- The UK 2012 drought led to a crop of blemished and smaller British fruit and vegetables – but Sainsbury's supermarket decided to relax their cosmetic quality standards and accept the uglier produce to help British farmers minimise financial losses. This was an informal arrangement organised ad hoc; however, a similarly formalised approach – enabling flexibility in cosmetic appearance of produce with changing weather conditions – may be welcomed by UK food producers.

- Some progress has been made in this area with some supermarkets rolling out wonky vegetable lines for some produce in 2016. This raises the question whether this could be more widely applied when there is drought to ease the financial pressure on producers.

**Source:** WWF and M&S, 2017; NERC, 2018

The CDP (CDP 2018) carried out a global assessment, including for the UK, of companies' exposure to water stress across their value chain and evaluated their water management processes and targets. The assessment found that despite almost a doubling of the number of companies setting targets to reduce water withdrawals over four years, there was an almost 50% rise in the number reporting higher water withdrawals. It is not clear how these high-level findings apply to use of water in the UK, but they do suggest a high level of risk to global supply chains from water scarcity (CDP 2018).

The LSE Climate Risk Business Survey (2020) found evidence of businesses investing in ecosystem services such as natural water storage to prepare for drought conditions, new water saving devices, and business continuity plans for water scarcity situations. The sample size is small, however, and it would be useful to see a national survey of businesses, particularly SMEs, to understand how widespread these actions are. The motivation for businesses to minimise their water use is attributed to a set of drivers (Zero Waste Scotland, 2020): The need to cut costs associated with water use, treatment and disposal; rising costs for water supply and disposal; more stringent legislative requirements associated with waste and water management; increasing consumer pressure resulting from environmental concerns; and the requirement to cut greenhouse gas (GHG) emissions (in particular, carbon dioxide) to improve the image of the organisation and help mitigate climate change. However, there is no overarching plan or target for any of the four UK countries at present.

#### 6.4.2.3 Adaptation shortfall (B3)

As set out above and below, there are promising signs of action by individual businesses and there are various Government programmes looking at improving water efficiency and reducing abstraction demand, but it is not clear, due to a lack of evidence, how this activity matches the scale of risk from climate change and whether there is or will be an adaptation deficit in the future (i.e. whether the policies and actions as planned could bring risk down to a low magnitude by the end of the century). Additionally, it is hard to determine the effects at the business level where businesses affected are reliant on public water supply over which they do not have control. Better data on trends in business water use (taking into account production) is needed as is an analysis of adaptation measures taken by SMEs and water intense manufacturing companies to understand the scale of risks. As explained in Chapter 4 there are also further steps that water companies can take to help close the adaptation shortfall (Chapter 4: Jaroszewski, Wood and Chapman, 2021).

#### 6.4.2.4 What are the barriers preventing adaptation to the risk? (B3)

There is limited evidence of sufficient adaptation levels. According to Waterwise (2018) the barriers to water efficiency adaptation for businesses include lack of awareness by businesses of risks and of

available water efficiency services; insufficiently strong financial motivations for seeking water savings amongst both businesses and water retailers; poor quality data on consumption; and a regulatory framework that has focussed wholesaler resources onto reducing household water use rather than business or non-household (NHH) use (Waterwise 2018). However, more data on production and consumption trends is required to understand the scale of the issue (MOSL, 2020). There is a lack of incentives amongst water retailers to provide customers this information. Moreover, firm-level data is hard to disaggregate given the reporting is done by SPID (supply point identifier), regardless of the scale of the business. Ofwat and Environment Agency (2020) also note lack of complete, accurate and timely meter reads, which can undermine retailers' and customers' ability to measure and manage water efficiency.

Also of note is that in England there are regulatory performance commitments with rewards and penalties on water companies to reduce domestic water use but nothing on business water use which has the effect of focusing their efforts on the former even when the latter may be feasible (Ofwat and Environment Agency, 2020). Direct abstraction of water by businesses has fallen in recent years, but progress in reducing consumption of the public water supply has stalled. It is not possible to tell whether businesses are becoming more water efficient without additional data on production trends.

Adaptation in some sectors may also have unintended consequences or pose risks of maladaptation. For instance, HR Wallingford (2020) find that adaptation in agriculture and other sectors may not lead to reduced water use. This is because new technologies or increases in fruit and vegetable production may require more water than is currently required. This impact will likely be greater the more the population grows.

#### 6.4.2.5 Adaptation scores (B3)

<b>Table 6.14</b> Adaptation scores for risks to businesses from water scarcity			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)

#### 6.4.3 Benefits of further adaptation action in the next five years (B3)

##### 6.4.3.1 Additional planned adaptation that would address the adaptation shortfall? (B3)

Watkiss *et al.* (2019) found that there are high benefits (although also high potential costs) of further action to reduce the risk of water scarcity. The costs and benefits do not just fall under the category of businesses but are part of a larger picture of action to reduce demand and increase supply across business, infrastructure, and households, with an aim of protecting and enhancing the natural environment.

Currently, there is a lack of incentives for water companies to help reduce commercial water use, and reduction efforts have been left to the retail market, unlike in the domestic sector. Further understanding of sectoral usage is required for this (Ofwat and Environment Agency, 2020). Water UK (2016) has estimated that a 'twin track' approach of demand management coupled with appropriate development of new resources and potential transfers is the most suitable strategy for providing drought resilience in the future. They estimated that total costs per annum for all potential future scenarios to maintain resilience at existing levels in England and Wales are between £50 million and £500 million per annum in demand management and new water resource options. If resilience to 'severe drought' is adopted, this increases to between £60 million and £600 million and for resilience to extreme drought (beyond the 1 in 100-year event) to between £80 million and £800 million per annum. In England a number of the policy measures that Defra consulted on in 2019 to reduce personal water use, for example, could also help increase business water efficiency and reduce water and energy use. Prime among these is water efficiency labelling of water using products linked to minimum standards for new build and retrofits which would realise significant benefits both for domestic and business water users (Defra, 2019).

One idea MOSL (2020) are looking at is to map out their data on business water users and overlay that data set with maps of current or future water stress areas the Environment Agency hold. This would help identify where efforts to reduce business use could be prioritised and what types of businesses/sectors could be targeted. Ideally this can be used to inform next round of water resource plans so a further adaptation action for the next 5 years. High consumption businesses can be incentivized monetarily, for instance through cheaper rates for businesses if they don't consume in the summer when peak demand is hard to manage.

Some of the key business benefits of handling water stewardship effectively include (WWF and M&S, 2017) reduced water related business risk, increased drought preparedness, reduced carbon emissions from supply and heating of water, continuity of supply from sourcing locations for retail businesses, cost savings associated with water efficiency, strong engagement with the local community, and reputational benefits.

WWF suggests there will be significant benefits to the UK from taking the following further actions (WWF, 2015): the UK government should share the evidence base, for example the Environment Agency's water and agriculture monitoring, widely with business and explore opportunities to help businesses identify key hotspots (e.g., showing impacts related to product type). To ensure there is a strong framework for the sustainable management of water WWF suggests more efforts to bring non-compliant farmers in England into compliance and ensuring basic legislation is sufficient to support further achievement of good health, as defined by the Water Framework Directive. Other suggestions focus on reforming abstraction licensing to ensure environmental needs are met as a function of every licence and that abstraction charges encourage efficient use; and continuing investment in the Catchment Based Approach including by exploring ways to encourage private sector support and funding (WWF 2015).

Stakeholder discussions as part of the UKCCRA3 stakeholder engagement indicate that a consistent methodology for measuring & reporting water use for products (water foot printing) is to be encouraged. There would be benefits to looking at whole life cycle approach to measuring water usage and make sure embedded water is fully taken into account in such reporting. The long-term

trends and pinch point analysis would provide useful tools for industry and Government to show where to focus efforts for either improved water efficiency of business or increased resilience of supply. The retail market could help to create incentives for businesses to become more water efficient but has so far only had a limited impact. The opening of the retail market for water offers multiple benefits for businesses but the potential effect on water efficiency is uncertain.

The CEO Water Mandate's Corporate Water Disclosure Guidelines offer a common approach to disclosure. They put forward metrics that can begin to harmonize practice and also provide guidance for defining what to report. These Guidelines have the potential to drive convergence and harmonization with respect to how companies report their water management practices while helping to minimize reporting burdens, thus allowing companies to allocate more time and resources to actively manage water. The list of endorsing companies as well as reports on their progress can be found online and are updated regularly (CEO Water Mandate, 2014).

#### 6.4.3.2 Indicative costs and benefits of additional adaptation (B3)

As highlighted above, there are studies which have considered the overall costs and benefits of national level action to reduce the risk of water scarcity. There are also a complementary set of demand side measures that can be introduced by businesses, many of which are no-regret and low-regret. As a general rule of thumb, reductions of 30% in water bills are usually achievable at little or no cost for sites that have not previously tried to save water, and as much as 50%, or more, if projects with capital investment payback periods of up to two years are included (WRAP, 2005). There are detailed cost-effectiveness assessments of measures for industrial sites, with indications of costs and payback periods. However, as highlighted above, there remain important barriers to address to encourage the uptake of such measures, which includes a role for government to raise awareness and create appropriate incentives. There is a strong case for Governments to consider adopting consistent national minimum levels of resilience, recognizing that there are significant issues to address, including inter-regional and inter-generational fairness. The investment needed to increase resilience appears relatively modest compared with the cost of drought. A twin-track approach that includes supply enhancement, with associated transfers, as well as demand management, is the most appropriate strategic mix for the future. There is a case for a national level adaptive plan that supports ongoing water company plans and balances risks against opportunities to defer costs. See also Chapter 4 (Jaroszweski, Wood and Chapman, 2021) and Chapter 5 (Kovats and Brisley, 2021).

#### 6.4.3.3 Overall urgency score (B3)

The current magnitude is low, with the potential for it to increase to medium or high in the longer term across the UK. It is assessed that the risk will only be partially managed in future. The growing risk of severe drought and limited understanding of trends of supply to and demand from businesses and effectiveness of policies and adaptation intervention, means that there would be benefits to further investigation in the next five years. The urgency scoring for water-related risks in Chapter 4 (Jaroszweski, Wood and Chapman, 2021) and Chapter 5 (Kovats and Brisley, 2021) is also relevant here.

**Table 6.15** Urgency scores for risks to businesses from water scarcity

Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further investigation	Further investigation	Further investigation	Further investigation
Confidence	Low	Low	Low	Low

#### 6.4.4 Looking ahead (B3)

It is critical to have better evidence for CCRA4. At present, the lack of sectoral usage and business level data means any analysis is high-level and has low confidence. With the new evidence through the CCRA-research project on future water availability (HR WALLINGFORD 2020) it should be assessed where supply-demand deficits in catchments across the UK exist, particularly where there are water-intense industries such as chemical, food/agriculture, and paper. Delivery of the Retailer Wholesalers Group action plan and outputs of the work MOSL are doing on business consumption data would provide further evidence for CCRA4. A systematic approach must be taken to connect business water scarcity with public water supply and infrastructure (Chapter 4: Jaroszewski, Wood and Chapman, 2021) and household water supply (Chapter 5: Kovats and Brisley, 2021) given the overarching regulation governing them. Similarly, water scarcity outside of the UK (Chapter 7: Challinor and Benton, 2021) is projected to critically impact supply chains but lies beyond the scope of this section. The extent of interconnectivity can be better captured in CCRA4.

### 6.5 Risks to finance, investment and insurance including access to capital for businesses (B4)

The current risk to finance, investment and insurance from physical climate impacts is medium across the UK and expected to increase. There is also a risk that access to capital for businesses will be negatively impacted by climate change through decline in availability and affordability of insurance, a reduction in the value of assets and investments, and increased credit risks and rising costs of capital for firms exposed to physical climate risks.

The exposure of the UK finance sector through international channels is currently medium, but going forward there could be further impacts on business models, products and flows of capital, leading to a higher risk to the stability of the financial system unless the risks are better managed and reduced. This is particularly important given the UK's strong role as a centre for the international financial sector. There is crossover with international risks to the UK finance sector, which are covered in Risk ID7 in Chapter 7 (Challinor and Benton 2021). The adaptation actions advocated in the CCRA2 Evidence Report like stress testing and scenario analysis, inclusion of liability risk and uptake of

green bonds to support adaptation have all been incorporated in government and private sector response to varying degrees. Whether or not this improved understanding is being translated into action remains unclear. The biggest change from CCRA2 is the shift in awareness, understanding, and reporting of risks, including recent Government announcements of making the Taskforce on Climate-Related Financial Disclosures (TCFD) reporting compulsory, indicating a shift in the regulatory approach, which in turn has implications on the behaviour of firms. However, despite a growing number of UK companies engaging in risk disclosure of climate risks, only a very small number of companies do this strategically or demonstrate how the newly gained understanding of physical risks is used in their financial and operational decision making. Internalizing climate risks and pricing it into insurance, lending or investment decisions will have implications for those relying on access to capital and insurance. Currently there is limited evidence of physical climate risks being a driver in pricing, but this could change suddenly in the wake of more frequent and more severe extreme events. Overall direct action to address risks is limited, which poses a challenge: Current lack of investment in physical risk reduction as well as underestimating physical damages and limited understanding of thresholds and interdependencies, particularly in the context of indirect impacts from physical risks, can create lock-in situations for the finance sector and those who depend on it. Another issue is the prevailing focus on averages rather than extreme outliers, which can generate a false sense of security across the sector. Regulators are now suggesting that companies conduct stress-testing for different scenarios. Initially this was limited to scenarios of 3°C global, but more recently this also includes scenarios of 4°C global warming, which no longer are dismissed as unrealistic.

#### 6.5.1 Current and future level of risk (B4)

Building on CCRA2, Surminski *et al.* (2018) warned that “access to capital may become material if credit becomes more expensive or limited for companies that are considered to be taking insufficient adaptation action. Similarly, availability and affordability of insurance cover can be affected by rising risk levels, which in turn would also have implications for business’ access to capital.” CCRA2 also noted potential risks for access to capital through primary channels (exposure of assets to climate hazards and increasing exposure of the insurance industry) and secondary channels (regulatory change in response to future climate, development of new tools to manage risks, changes in credit ratings and changes in market expectations and investor behaviour). Here we revisit these risks and consider the new evidence base for risk and adaptation action. Importantly, risks for some also present opportunities for others. One can broadly distinguish between risks and opportunities to financial services arising from sudden and slow-onset physical risks, such as increased losses for insurers but increasing insurance needs, reduced value of real-estate assets but increased infrastructure investment needs and mortgage defaults but growing capital needs for resilience. Some of these longer-term opportunities are covered in B7.

#### 6.5.1.1 UK –wide current and future risk (B4)

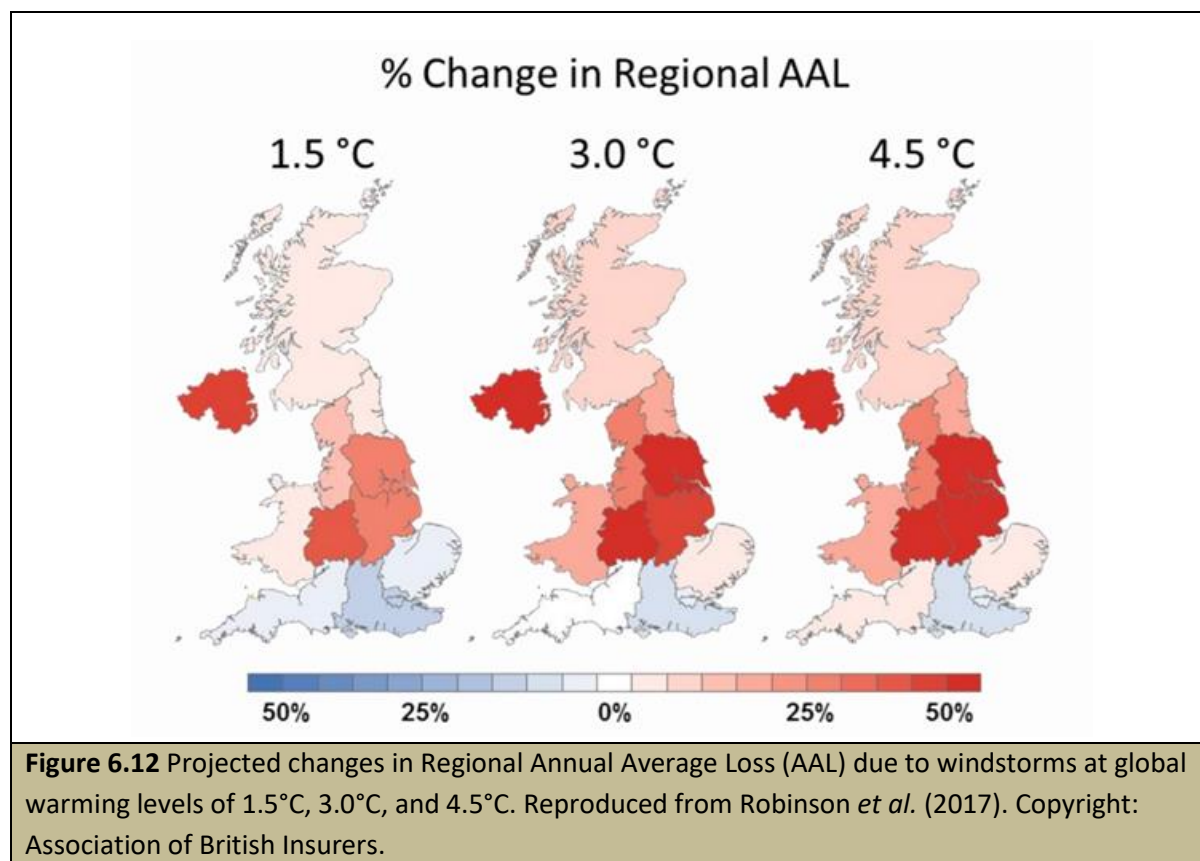
Note: it has not been possible to split the evidence by UK country for this risk.

A detailed analysis of climate hazards is provided in Chapter 1 (Slingo, 2021). Here we are looking at evidence of the implications for the financial system across the main hazards of floods, windstorms, subsidence and global risks, before exploring how these hazards may impact different parts of the financial system (6.5.1.2-6.5.1.5).

**Flooding.** In terms of domestic risks, flooding is the most significant risk for the financial system (Bank of England, 2018) with financial impacts on insurance, mortgages and investment (see below). See sections B1 and B2 for flood specific assessments.

**Windstorms.** The impact of UK windstorms is less clear. It is recognized that storms are having a significant impact on businesses through damage and disruption to business infrastructure, which can lead to an immediate financial shock to the business, requiring investment and access to capital. This is seen in the damage to Gatwick Airport's North Terminal due to multiple storms, which led to £250,000 in direct costs (Acclimatise, 2018). In Wales, £100,000 was spent by the Welsh government for the clean-up of the Holyhead marina, where 80 boats were destroyed by storm Emma in 2018. Further major investments are expected for the reconstruction of the site (Welsh Government, 2018). Initial ABI estimates for windstorm damage pay-outs from the 2020 storms Ciara and Dennis are £149 million, with 61,000 domestic property claims, totalling £77 million, 9,000 commercial property claims at £61 million, and 3,500 motor claims at £11 million (Insurance Journal, 2020). However, there are some future trend studies (UNEP-FI, 2019, CISL, 2019) that indicate a reduction to windstorm losses in the UK under future climate scenarios. Figure 6.12 illustrates that windstorm loss projections are region specific, with areas of increasing loss particularly in the North of England and Northern Ireland and decreasing loss in the South of England (Robinson *et al.*, 2017). This paper looked at different RCPs and projected the changes in frequency and intensity of windstorms, looking at the average annual loss (AAL), i.e. annual insured loss aggregated over an entire year, the 1.0% exceedance probability (100-year) loss, and the 0.5% exceedance probability (200-year) loss. The results indicated a change in the overall AAL of 11%, 23%, and 25% for global warming levels of 1.5°C in the 2050s, 3.0°C in the 2070s, and 4.5°C in the 2090s, respectively. The analysis also indicated a possible increase of up to 30% in the 100-year return level loss and up to 40% in the 200-year return period loss with 4.5°C warming in the 2090s, though the distribution of these changes are not equal across the country.





**Subsidence.** With regards to impacts of drier weather insurers have seen a rise in subsidence claims due to hotter and drier weather (Financial Times, 2018). Chapter 4 (Jaroszewski, Wood and Chapman, 2021) assessed the current and potential future subsidence risks. The Association for British Insurers (ABI) reported after the 2018 heatwave that over 10,000 UK households made claims totalling £64 million in only 3 months (July, August, September) (ABI, 2018). These were the highest reported figures since the 2003 and 2006 heatwaves. Subsidence has impacts on building stock and financial implications via insurance/non-insurance and mortgage defaults. Shrinkage and swelling of clay soils is the most common foundation-related cause of damage to low-rise buildings in the UK, and subsidence can be attributed to changes in temperature, humidity, solar radiation and wind speed (Sanders and Phillipson, 2003). In the UKCIP02 projections with a range of emissions scenarios, soil moisture is projected fall by between 20 and 40% in South East England by the end of the century, increasing the incidence of subsidence (Sanders and Phillipson, 2003). This will impact both existing building stock as well as construction of new buildings. Sanders and Phillipson (2003) claim the insurance industry may be expected to have a significant role in the improvements in build quality by refusing to insure substandard properties, if subsidence rates increase. BGS have applied the latest UK Climate Projections (UKCP18) scenarios for rainfall and temperature changes in the UK for the next century, with maps produced for the south-east of England. This shows areas with varying vulnerability to shrink–swell and thus subsidence in the future due to climate change. The maps show that areas with clay soils that shrink and swell with changes in moisture are projected to become increasingly susceptible in the coming century and beyond (BGS Research, 2020).

**Global risks.** In global terms, the UK is one of the most exposed countries due to its high financial leverage and high centrality in the global financial network (Mandel et al, 2020). The UK is also one

of the leading insurance markets globally, underwriting risks all over the world and across sectors with complex supply chains. The UK is currently the leading exporter of financial services across the world. In 2018, The UK's financial services trade surplus of \$82.7bn (equivalent to £61.9bn) was nearly the same as the combined surpluses of the next two leading countries (the US and Switzerland) (TheCityUK, 2019). This presents both greater risks and opportunities for the UK financial market. The interconnectedness of markets is increasing – for example, the effect of the Thailand floods in 2011 to the manufacturing sector cost USD\$2.2 billion in insurance claims for Lloyds of London (Lloyds, 2012). In 2019, direct economic losses and damage from natural disasters were \$232 billion, with 409 total natural disaster events (Aon, 2019).

#### 6.5.1.2 Risks arising from availability and affordability of insurance (B4)

Rising physical risk levels are already threatening insurability as well as affordability of existing cover: higher claims costs will require a higher premium, which may jeopardize affordability, largely due to the financial dynamics of disasters. Mandel et al (2020), highlight that the size of insurance buffer is critical to ensure that the insurance risk is not being passed on to the financial sector. One issue of increased climate risk is the resilience of the long-term business model of the insurance sector and the potential inability to set premiums high enough to account for the risk and loss in revenue (Surminski, 2020). In the case of floods, premiums might indeed be expected to rise on average, as markets continue to fluctuate in response to climate change (Westcott et.al., 2020). This is partially due to the nature of floods; as a concentrated and correlated risk, floods require insurers to hold a lot of liquidity, which in turn requires that they charge a higher premium (Financial Times, 2020b). Past modelling cannot always be used for predictions and focusing on averages can lead to distorted risk assessments (Swiss Re, 2020), however since CCRA2 there has been significant development predicting future losses, including new models, platforms and assessments such as the OASIS initiative; see also the Natural Hazards Partnership (NHP) (Hemingway and Gunawan, 2018). An example of insurer-led assessment of risk and pricing implications is the framework presented by Institute and Faculty of Actuaries (2019), using the example of Aviva's UK flood assessment and insurance stress test experience.

A recent study models future insurance affordability to floods across Europe, including for the UK (Tesselaar *et al.*, 2020). This finds the effects of climate change will vary across the Member States, because they use different flood insurance models, but projects high levels of unaffordability across the continent. The increase in flood risk under climate change may cause substantially higher risk-based insurance premiums, which makes it less attractive to purchase flood insurance, and this exacerbates inequality problems with the affordability of insurance for low-income households. This study finds rising unaffordability and declining demand for flood insurance especially towards 2080. This happens under all climate scenarios, but it is especially high under a 4°C scenario (Tesselaar *et al.*, 2020). The higher the projected climate warming, the more extensive the implications for the sector. Simply put, AXA CEO comments, "A +4°C world is not insurable" (AXA, 2017). As reported in Aviva's recent climate disclosure report: "The physical effects of climate change will result in more risks and perils becoming either uninsurable or unaffordable." (Aviva, 2019). Only a small proportion of natural disaster events are currently insured – termed the 'protection gap', this disparity presents a significant business opportunity for insurers. In 2019, worldwide economic damage from flooding was \$82 billion, with only \$13 billion of that being insured (Financial Times, 2020b). One opportunity

with high growth potential is that of insurance-linked securities (ILS). Also known as catastrophe bonds, ILS enables insurers to transfer large and complex risks, such as catastrophic risks arising from natural disasters, to capital markets rather than through reinsurers. The capital that is backing ILS stands at around \$90 billion globally, and research by Ernst & Young (EY) estimates that this market could grow to a value of \$224 billion by 2021 – 28% of reinsurance capital as a whole (Green Finance Initiative, 2018).

With regards to current risks in the UK there is no evidence in a shift of overall insurability, but there is evidence of localized issues, for example after the 2019 floods, which triggered the Blanc review on the availability of flood insurance (Defra 2020). Recent business surveys including the LSE Climate Risk Business Survey (2020) indicate that some businesses are experiencing increased costs of insurance for physical climate risks, but overall availability and affordability concerns are relatively low, except for SMEs (CCRA stakeholder engagement; Surminski, Merhyar and Golnaraghi, 2020). However, going forward this is expected to change: recent reports highlight that with better risk disclosure and reporting the cost of insurance could increase and reduce company values by 2-3% (Economist, 2019). This corroborates with Schrodgers' (2018) findings that insuring against physical risk could cost companies 4% of market values. Increasing costs of insurance is also expected to reduce demand and uptake, intensifying the current trend of underinsurance or non-insurance: Globally, only 50% of losses are insured, and non-or underinsurance is expected to increase as extreme events become more frequent. Insurance models suggest that if extreme events with an exceedance probability of 1 percent manifest, non-or underinsurance could be as high as 60 percent (McKinsey, 2020).

Overall, as per Bank of England (2017), UK insurers are well placed to deal with current risk levels but less so for future risks: "insurance firms are reasonably well equipped to manage the current level of physical risks to the liability (claims) side of their balance sheets. At the same time, continued diligence is required, particularly if, as expected, the impacts of climate change drive greater volatility and higher potential losses" (Bank of England, 2017).

#### 6.5.1.3 Reduction in the value of assets for investors and stranded assets arising from physical risks (B4)

There is a possibility of stranded assets due to physical risks. As IADB (2020) outline, assets can be stranded as a result of environmental challenges and changing resource landscapes. For example, coastal flooding may produce stranded assets like port facilities and railroads if left unmanaged (Buhr, 2017). Physical climate risks can also strand assets throughout the agricultural supply chain (Caldecott et al, 2013). Whilst many fund managers are offering equity strategies with low-carbon options, there are few tools available to reduce stranding risk for other asset classes (IADB, 2020). Value impairment may not instantaneously lead to SA classification. However, stranded assets can have negative credit consequences, as seen in the case of asset impairments in the German utilities sector in 2013 (EY, 2014). Write-downs can occur due to high exposure to natural hazards and high adaptation costs for retrofitting (EU-CRREM, 2019). Thus, asset damages can directly affect the longevity of physical capital due to increased speed of capital depreciation (BIS, 2020).

These risks are in addition to SA risk due to transition, litigation, regulation and behavioural changes discussed earlier in this section (Carbon Tracker, 2017; EU-CRREM, 2019). There are also discrepancies with regards to the value of stranded assets with some estimates focusing on the

value of fossil fuel assets whereas others focus on stranded capital (losses related to the capital invested in a project subject to stranding) (BIS, 2020).

According to the Carbon Disclosure Project, firms anticipate a potential \$250 billion of asset loss due to climate change, while \$1 trillion is at risk over the next five years, of which 80% is in the financial services sector (CDP, 2019). In this context, the Coalition for Climate Resilient Investment has been mobilising since its launch in 2019 to develop methods for assessing and including physical climate risks in investment decision-making, with the objective of creating climate resilient economies (CCRI, 2019). Recognizing risks is not only important to devise strategies for greater resilience of investments, it also provides investment opportunities in various new asset classes such as green bonds, low-carbon or fossil-fuel equity, sustainable public or private equity and sustainable infrastructure (Association of British Insurers, 2019; Mercer, 2019). Opportunities are discussed in risk B7.

Importantly, current physical risks to assets are not considered material if they are insured. This dependence on insurance poses systemic risks and can trigger financial instability should affordability or availability of cover change, as first reported by the insurance regulator PRA in 2015 (BoE 2015). This interplay between physical risks, insurance and finance is particularly visible in the context of real estate – where mortgage providers as well as real-estate investors rely on insurance to protect them from losses arising from physical risks (Westcotte et al., 2020).

Real Estate is a significant asset class (Bikakis, 2020), as the size of the professionally managed global real estate investment market was worth US\$9.6 trillion in 2019 (Teuben and Neshat, 2020). Mercer's Modelling the Investment Impacts of Climate Change tool (Mercer, 2019) identifies real estate, infrastructure, agriculture and timberland as the sectors showing the greatest negative sensitivity to the impact of physical damage. While for equities, physical risk sensitivity is most negative for utilities and energy, but some sensitivity is relatively widespread across sectors, including industrials, telecoms, financials, and consumer staples and consumer discretionary (Mercer, 2019). UNEP-FI's analysis of physical risks to real estate assets note that buildings provide valuable income and capital appreciation possibilities to investors, but, as long-life fixed assets, face unique climate change related physical and transition risks (UNEP-FI and Acclimatise, 2018). With their relative illiquidity compared to many other asset types, and from their physical permanent locations and long investment cycles, it is essential that real estate owners and managers identify long-term climate change trends and take adequate risk mitigation measures to maintain and enhance value. (UNEP-FI, 2019) The report conducts 1.5°C, 2°C, and 3°C global warming scenario-based analysis of sudden and slow-onset physical risks as well as transition risks. The analysis combines historic loss data and future climate models with information about exposure and vulnerability to provide financial information to real estate investors. An important observation is the need to consider regional differences: "From a physical risk perspective, while average risks can be low, certain buildings may be high risk from one or more hazards. Assessing the outliers can allow investors to mitigate risks for particular assets by ensuring that building design is fit-for-purpose; transferring the risk through insurance; or, at the extreme, offloading the risk by selling the asset." (UNEP-FI, 2019) This is also a conclusion from the Cambridge Institute for Sustainability Leadership (CISL) report into climate modelling for real-estate portfolios that shows significant increases in

losses impacting real-estate assets due to changes in windstorm and flooding hazards as outlined in Box 6.3.

**Box 6.3.** Recognising risks in investment portfolios. Source: CISL, 2019.

- For investment portfolios in the UK, the increase in AAL is 40 per cent.
- For investment portfolios, in a 4°C warming scenario, the increase in AAL from flood risk across four UK portfolios is modelled to be 70 per cent higher in the 2050s than today.
- Especially in a 4°C warming scenario, the modelling finds significant differences in the risk of different portfolios of mortgage and investor assets.
- UK flood risk by investment portfolios is a 70% increase in AAL by 2050s if warming continues to 4 degrees by portfolios of mortgage and investor assets.

See also Westcott et. al. 2020.

**Box 6.3 Table 1.** Modelling shows increased losses are expected across all perils, but they are lower if global efforts to reduce emissions are successful. Reproduced from CISL, (2019).

Peril	Asset type	Risk Metric	2°C warming by end of century	4°C warming by end of century
UK flood risk	Residential mortgages	% Increase in AAL by 2050s	61%	130%
		% increase in number of properties at significant risk of flooding (annual probability of 1.3% or above)	25%	40%
UK flood risk	Investment portfolios	% Increase in AAL by 2050s	40%	70%
North America and Pacific Rim tropical cyclones	Investment portfolios	% Increase in AAL by 2050s	43%	80%
European winter windstorms	Investment portfolios	% Increase in AAL by 2050s	6.3%	3.6%

Market intelligence provider Four Twenty Seven and real estate technology company GeoPhy have partnered to assess the exposure to the physical impacts of climate change of 73,500 properties owned by 321 listed Real Estate Investment Trusts (REITs) Four Twenty Seven and GeoPhy, 2018). Main findings include that 35% of REITs properties are exposed to climate hazards. Of these, 17% of properties are exposed to inland flood risk, 6% to sea level rise and coastal floods, and 12% exposed to hurricanes or typhoons (Four Twenty Seven and GeoPhy, 2018).

#### 6.5.1.4 Risk of increased cost of capital (B4)

The risk of increased cost of capital is currently low, however evidence is hard to establish as some institutions adjust their capex (capital expenditure) required for adaptation or climate transition, without detailing climate risks (Colas et al., 2019). Moreover, cost of capital depends on the size of the business, with barriers higher for SMEs (NDF, 2020; UNEP-FI, 2016). Capital requirements are usually calculated on a one-year horizon and are based on credit ratings that rely on historical records of counterparties. Nonetheless, due to climate risks, future capital requirements may not be the same as current capital requirements, creating discrepancies (BIS, 2020).

Future impacts from extreme weather events are expected to increase capital costs due to impairment of fixed assets, inventory write-downs, costs of repair, retrofitting and acquisition of new sites (EBRD & GCECA, 2018). Businesses can also experience employment or asset shocks from natural disasters transmitted via banks, mainly banks with less regulatory capital (Rehbein, 2018). The CCRA3 stakeholder discussions and the LSE Climate Risk Business Survey (2020) indicate that a number of businesses are expecting a future increase in the cost of capital due to rising climate risks. Future increase in capital costs are expected to drive capital reallocation from productive investment to adaptation capital, and drive investment from high risk investments to low risk. Reallocation from “brown” (or carbon-intensive) to “green” (or low-carbon) assets is also expected to occur (BIS, 2020). Increased capital costs can threaten price stability and cause supply shocks, which can have inflationary effects (BIS, 2020). Capital costs are expected to be most significant in the case of tail risks, as capital in institutions will be insufficient to absorb climate-related losses. There are also some opportunities for returns on capital and value creation resulting from sustainable operations, value chains and green sales and marketing (UNEP-FI, 2017). For example, Mercer (2019) found that investment in climate-resilient infrastructure can increase upfront capital costs by roughly 5%. However, resilient infrastructure can generate lower operating costs over the life of the investment and reduce repercussions of longer-term hazards.

#### 6.5.1.6 Risk of lack of private sector finance for adaptation (B4)

A further link between finance and physical risks is the flow of capital, which can either increase risk levels (for example through risk-insensitive investments or into high-emissions sectors) or help manage and reduce risks (for example through private sector finance for adaptation and low-carbon investments). Globally, the Global Commission on Adaptation calculated necessary adaptation investments between 2020 and 2030 of \$1.8 trillion, equivalent to less than 1 percent of projected total gross fixed capital formation in the period (McKinsey, 2020). While a significant chunk is projected to come through public investments, this sheer scale shows that private sector capital is essential in financing the transition to a climate resilient future, similar to what’s needed in the transition to a low carbon economy. There is evidence that a lack of adaptation and resilience metrics is a key constraint for channelling capital into adaptation and resilience investment opportunities. There are a number of initiatives in place to address this challenge, such as the Carbon Bonds Initiative “Principles for Resilience Investment” and a Climate-KIC project “Real Estate Climate Asset Mapping”, which is developing models for investors in real estate on transition and physical risk. The concept of the triple resilience dividend (Tanner et.al .2015; Surminski and Tanner 2016; Roezer et.al. 2021), i.e. the net co-benefits from investing in increased resilience, is being used to guide investment decisions towards more resilient structures. The payback of such investments is

estimated to be high, averaging a 4:1 return (CCRI, 2019), but there is still significant underinvestment in adaptation and resilience (UNDRR 2019).

While underinvestment poses a current risk, there are also signs that adaptation and resilience are being recognized as strategic objectives under the banner of ‘green finance’ as the UK Government acknowledges the need for more government support ‘to unlock new revenue streams in areas such as natural capital, carbon finance and resilience’ (BEIS, 2019). The Green Finance Strategy, published by Government in 2019, identifies resilience and adaptation as objectives “to align private sector financial flows with clean, environmentally sustainable and resilient growth, supported by Government action” (BEIS, 2019). Despite this recognition, the government does not provide further details on providing funds or financial mechanisms for these goals. More broadly, the CCC’s adaptation progress report (CCC, 2019a) notes that there is no overarching resilience investment plan and the available data does not demonstrate the extent to which businesses are realising the opportunities from climate change. Inclusion and clarification of the role of adaptation and resilience investments as part of efforts to agree on a sustainable finance taxonomy (European Union, 2019) is also important in order to enable private sector finance to support resilience.

Identifying synergies between adaptation investment and mitigation investment can provide opportunities for a two-pronged approach undertaken by the private sector (Mckinsey, 2020). There is evidence that physical risks and resilience are starting to be considered within a wider green finance landscape where the UK finance sector has clear opportunities (UK Government, 2018). The Department for Business, Energy and Industrial Strategy (BEIS) and Her Majesty’s Treasury (HMT) convened the Green Finance Taskforce, bringing together leading experts from the financial sector, academia and civil society to provide recommendations to support the delivery of our strategic objectives in green finance. This now also considers climate resilience and physical risks: “Green finance is about both clean growth and resilience; in addition to maximising the opportunity presented by the global transition to a low-carbon economy, the UK must also be resilient to the physical threats of climate change” (Green Finance Taskforce).

In CCRA2, green bonds were mentioned as a future opportunity to be realised by governments. The UK has nearly 80 green bonds already listed on the London Stock Exchange, raising more than US\$24bn. Green bonds have focused on mitigation to date (Climate Bonds Initiative, 2020), and there is no information on the level of resilience bonds. However, the first major resilience bond (\$700 M) was recently launched by EBRD<sup>10</sup>. This is a clear opportunity for the UK to use multi-lateral expertise, especially harnessing “catastrophe risk modelling firms, specialist credit ratings and accounting teams and financial regulators and research teams” (Green Finance Initiative, 2018).

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<sup>10</sup> Note that there are different types of resilience bonds. This can be a standard bond, i.e. a debt instrument to raise finance for investing in resilience (as in the EBRD resilience bond). However, there are also resilience bonds which are a variant of catastrophe bonds, designed to help manage the financial risk from catastrophes, while simultaneously promoting investment in infrastructure that mitigates physical risk (Vaijthala and Rhodes, 2018).

In addition, the CCC's progress report (CCC, 2019a) highlights the opportunities to lending and advisory services and green 'securitisation', which will help provide finance from institutional investors, and opportunities for banks as underwriters or issuers of green bonds. This also extends to natural capital – UK is a leader in knowledge and services for natural capital as highlighted in 25 Year Environment Plan, which will build on the Green Finance Taskforce to further explore opportunities for the financial sector to fulfil opportunities in natural capital and environmental protection. Recent developments that indicate UK firms and regulators are capitalizing on opportunities include Flood RE, the Centre for Disaster Protection (funded by DFID and WB), data hubs such as OASIS, and the funding for a new centre on Climate and Environmental Risk Analytics for Resilient Finance by the Natural Environment Research Council in 2021.

Banking and green finance have the potential to direct more finance towards adaptation and develop new adaptation products and services. One example of this is private sector engagement in the UK with flood protection schemes and partnership funding of resilience measures (Surminski, Mehryar and Golnaraghi, 2020). Further opportunities for the financial sector arising from adaptation is explored further below for opportunity B7. And Section 7.10 of Chapter 7 (Challinor and Benton, 2021) explores further opportunities internationally for investment into adaptation and mitigation for UK based firms, and the international leadership position the UK has developed.

### 6.5.1.3 Lock-in and thresholds (B4)

#### 6.5.1.3.1 Are there lock-in risks?

The main risks of lock-in are associated with long-lived investments that have a degree of irreversibility. This can include financial investments, thus there is a risk of lock-in to those that provide the capital for these investments, i.e. the financial markets, and in particular the risk of stranded assets. While these have been explored more in the mitigation domain (Caldecott, 2021) there are some increasing areas of potential risk for climate risks. These issues may be made more acute by other factors (e.g. insurance affordability) or for specific investment classes (e.g. property portfolios). These issues can include lock-in risks that occur from investments in the UK, but more difficult to capture, lock-in risks associated with investments overseas, especially in countries where climate risk profiles are much higher.

There are significant lock-ins where current action or inaction means that magnitude of future risk will be higher. Risk creation through risk-insensitive behaviour is a key issue: Examination of insurance data shows that most financial losses from natural disasters has come from greater exposure rather than increases in the climate hazards themselves which highlights that there is a significant amount of risk creation through non-risk sensitive investment (McKinsey, 2020). In the face of projected climate change impacts in the future this current trend can be expected to increase the magnitude of risks significantly. Another lock-in can arise from underestimating risks: While the use of climate risk assessments for disclosure and regulatory purposes is increasing, there are still significant limitations when interpreting or comparing results from different methodologies (Mercer, 2019). The magnitude of physical damage results is likely underestimated, and therefore it is important to understand model assumptions, data limitations and treatments of timeframes, asset classes and other risk factors when interpreting the model output. Whilst scenario analysis can be



conducted to predict physical impacts of climate change, psycho-social dynamics cannot be predicted. Moreover, the lock-in to certain policies and technologies remains uncertain. Therefore, understanding the true extent of financial market response to climate risks remains complex (CISL, 2015). Communication in terms of climate scenarios brings key limitations (Mercer, 2019), and firms are locked-in to existing accounting standards which fail to capture the extent of non-financial risks such as climate change, which may lead to underestimation of risks (Deloitte, 2017, GRI 2020). With these interconnected financial risks, businesses can experience employment or asset shocks from natural disasters transmitted via banks, seen mainly via banks which are disaster-exposed and with less regulatory capital (Rehbein, 2018).

#### 6.5.1.3.2 Are there potential thresholds? (B4)

As per CISL (2015), “climate change policy, technological change, asset stranding, weather events and longer- term physical impacts”, can all cause threshold effects for which investors are not prepared. The insurance industry has indicated that 4°C warming presents a threshold, beyond which insurability would be severely constrained (Tesselaar *et al.* 2020). Examples of biophysical thresholds include limits to insurability as the frequency and scale of extreme weather events becomes common (ABI, 2019). In the real estate market, lenders may bear some of the risk if the homeowners default. This is observed in Florida, USA, where asset repricing and losses from flooding could devalue exposed homes by \$30 billion to \$80 billion, or about 15 to 35 percent, by 2050, all else being equal. Therefore, “current levels of insurance premiums and levels of capitalization among insurers may well prove insufficient over time for the rising levels of risk” (Mckinsey 2020). If threshold effects are breached, Mckinsey (2020) note there can be large knock-on impacts on local economies tied into financial systems. This is particularly true if people, assets or industries affected are central to the economy. Current climate scenario analysis does not necessarily assess low likelihood, high impact extremes scenarios and therefore is likely to hide potential exposures and vulnerabilities. The proposed Bank of England climate stress tests offer an opportunity to address this and could include higher impact and lower-probability physical and transition risks. This would include thresholds and non-linearities and capturing climate, social and policy changes lying outside the central estimates of the probability distributions (Grantham Research Institute, 2020). Threshold effects will persist unless longer-term investment horizons are considered. As per a response to stakeholder discussions, even conducting a stress test to bond prices that is climate-related is projected to yield inconsequential results compared to other short-term risks that most businesses face.

Another aspect raised in discussions with the insurance sector during our CCRA3 stakeholder engagement activities was the heavy reliance on general insurance as an adaptation mechanism, and the need to include life insurance in risk assessments. This is especially true for climate scenarios with extreme weather, such as extreme heat (Risk B5) or severe flooding and storms (Risk B1 and Risk B2) which could increase mortality and morbidity. There is also a need for greater focus on low likelihood, high impact risks of climate change. Whilst there is some analysis (Mandel *et al.* 2020) addressing climate impact assessment on the risk of catastrophic outcomes, this requires further attention.

#### 6.5.1.4 Cross-cutting risks and inter-dependencies (B4)

CCRA2 called for more research into interacting risks. These are also important for the impact on the financial sector, given the close interplay with the real economy and the danger of systemic risks through overreliance on insurance and under-estimating physical climate risks. However, these are still not well understood and lack recognition in current assessments. This includes lack of multi-hazard assessments, no quantification of indirect risks and impacts, and limited analysis of interplay between transition, physical and liability risk. This is a key challenge, as these interdependencies can potentially have significant influence on the magnitude of risk. The occurrence of multiple risk factors in a particular geography, like high reliance on a particular sector and exposure to multiple hazards, will make the ability to finance adaptation investments non-linear (Mckinsey, 2020). Climate change is a meta-risk, as opposed to a risk silo, and must always be viewed multilaterally. The amplification of climate-related shocks in the financial system is also conditional on the reaction of actors in play. For instance, the propagation mechanism depends on sequential reassessment by financial institutions of counterparty associated risks (Mandel et al, 2020).

#### 6.5.1.5 Net-Zero implications (B4)

Delivering Net Zero will require significant investments, including in infrastructure and building retrofit (see also Chapter 4: Jaroszweski, Wood and Chapman; and Chapter 5: Kovats and Brisley, 2021). Without attention to future climate risks, this could create broader vulnerabilities which could increase this risk. Instead, investment in net zero and climate resilience should go hand in hand and mutually reinforce the ambitions of low-carbon and resilience.

#### 6.5.1.6 Magnitude scores (B4)

The magnitude scoring for Risk B4 (Table 6.16) is based on the evidence presented above and our expert judgement. While insurance absorbs a large amount of the current risks this is still scored at medium given the overall economic scale of damages (£ tens of millions for the UK). The future magnitude is expected to increase across the UK compared to current risk, with medium magnitude for the pathway to 2°C global warming by 2100 and high for 4°C global warming at the end of the century (£ hundreds of millions economic damage and foregone opportunities for the UK). Confidence is medium for the 2050s for the 2°C warming pathway, low for that time on the pathway to 4°C global warming, and also low for the 2080s on both pathway, reflecting that there is still more focus and subsequent evidence for near-term impacts on a pathway to 2°C global warming. The magnitude of risks can substantially increase given the lock-ins, threshold effects and interaction of risks. Moreover, future risks are expected to increase as more businesses face financial impacts such as substantial losses or exit from the market due to high insurance claims. This is also reflected in the finance community's own perception of risk, as seen in the World Economic Forum Global Risk Report (2019). It is expected that the increasing use of climate scenario analysis and climate stress testing by financial sector companies will provide further insights into the magnitude scoring.

**Table 6.16** Magnitude scores for risks to finance, investment and insurance including access to capital for business.

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	Medium	High	Medium	High
	(Medium confidence)	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Medium	Medium	High	Medium	High
	(Medium confidence)	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Medium	Medium	High	Medium	High
	(Medium confidence)	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Medium	Medium	High	Medium	High
	(Medium confidence)	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)

## 6.5.2 Extent to which the current adaptation will manage the risk or opportunity (B4)

### 6.5.2.1 Government and regulatory action (B4)

#### 6.5.2.1.1 UK-wide

The overall aim of government intervention is to protect financial stability and strengthen the resilience and competitiveness of the UK financial sector. Over the last two to three years there has been a significant increase in regulatory activity to encourage physical risk analysis and disclosure across the financial sector– framed in a voluntary and exploratory context and focused on governance related aspects– which is encouraging firms to internalize climate risks, including physical risks. For example, banks and insurers in the United Kingdom are now required to allocate responsibility for identifying and managing climate-related risks to senior management functions (PRA, 2019). Moreover, Power et al (2020) note that Bank of England’s Prudential Regulation Authority’s statement (PRA, 2019b) suggests that firms should expect that disclosure will be mandated in the near future. This is potentially critical as, contrary to mitigation, companies are often reluctant to share information on adaptation: Not only can adaptation measures and their benefits be more difficult to communicate, the information could be a source of competitive advantage or disadvantage (WBCSD, 2019; Agrawala et al., 2011). From a regulatory angle, UK regulators are also reporting under the Adaptation Reporting Power on their activities taken to

strengthen preparedness to climate change. This triggered the early assessments of climate risks conducted by the insurance regulator PRA (Bank of England 2015). The Government's UK Green Finance Strategy published in 2019 mentions physical risks and resilience, and highlights opportunities for insurance domestically and abroad, particularly given the level of non-or underinsurance of assets.

The Government has also pledged to promote the greening of the financial system internationally. This included taking a leadership role on the adaptation and resilience strand at the United Nations (UN) Climate Action Summit which built on earlier work of the Green Finance Taskforce. The Government's Green Finance Strategy could become an opportunity to direct more finance towards adaptation, as recommended in the CCC Progress Report (2019a).

In addition, the Government has committed funds to address information gaps (highlighted in the Green Finance Taskforce report) (2018) that set out the need for a climate analytics centre. As stipulated, the research council UKRI-NERC and Innovate UK will allocate £10m over the period 2020/21 –2024/25 to develop a new institutional framework for scientifically-robust, open-access climate and environmental risk (CER) information to support the financial services sector to materialise these risks on the balance sheet. Overall, the ambition of the programme is to support innovation and private sector investment in the development of new CER information services for the financial services sector. This will inform disclosure and decision-making to enable more effective, efficient, and sustainable allocation of investments, reduce climate and environmental change-related losses, and stimulate economic growth in the CER services sector and related green finance products.

Other governance-supported initiatives include the Coalition for Climate Resilient Investment (CCRI), created in 2019 by the UK Government alongside private actors to support:

- National decision-making – by facilitating an understanding of the economic and social value at risk associated to physical climate risks;
- Project valuation and investment appraisal – by providing investors with greater predictability of longer-term cash flows;
- Financial innovation – by identifying innovative taxonomies for financial instruments capable of guiding a more efficient allocation of capita.

In particular CCRI aims to address inconsistent approaches to the assessment of risk in time horizons relevant to investment decision-making which constitute a case of imperfect information, and market failure. It capitalises on the momentum of TCFD to provide solutions in investment decision making and has numerous UK-based businesses and institutions onboard like Willis Towers Watson, Aberdeen Standard Investments, Schroders, HSBC, Arup, Mott Macdonald and The Prince's Accounting for Sustainability Project.

Other regulatory changes that have targeted the UK financial sector have had impacts in terms of disclosure, the level of analysis and internal governance processes, as well as collaboration between companies and regulators. One example of collaboration is the Climate Financial Risk Forum, where financial services companies and the regulator come together to explore key issues related to

climate risk. The forum is organized through four technical working groups on disclosure, scenario analysis, risk management, and innovation (FCA, 2020).

Section 7.10 of Chapter 7 (Challinor and Benton, 2021) explores further the UK's involvement in climate finance on the international scale.

Business and financial regulation are reserved matters, however some specific actions at the devolved level are also highlighted below:

#### 6.5.2.1.2 England

The assessment above for the UK also covers England as most are being led by the Department for Business, Energy and Industrial Strategy, and there are no separate 'England-only' initiatives. The second National Adaptation Programme (2018) notes the very wide-ranging goal from Defra's 25 Year Environment Plan to "ensure that all policies, programmes and investment decisions take into account the possible extent of climate change this century" and discusses the role of green finance as set out above. The specific actions listed in the appendix to NAP2 relevant to this risk include taking forward the Government's Greening commitments, working with the British Standards Institute on resilience standards (now published) and the recommendations (at the time) of the Green Finance Taskforce.

#### 6.5.2.1.3 Northern Ireland

The second Northern Ireland Climate Change Adaptation Programme (DAERA, 2019) highlights that businesses in Northern Ireland (99.9% of which are SMEs) are being impacted by severe weather, and lists actions related to helping businesses adapt to climate impacts. Specific actions in the programme are targeted at particular sectors (water and energy) as well as provision of guidance. There are no actions specifically listed for the finance sector.

Technical consultancy is available to businesses from Invest Northern Ireland with an annual energy and resource spend in excess of £30k. This support consists of fully funded technical audits, feasibility studies and advice, complete with a report and recommendations to help participating businesses identify cost savings. Specialist areas of support include aspects that touch on physical risks from climate change; energy management and efficiency; resource efficiency including water and waste management; transport and logistics; sustainable business collaborations; clean technologies; investigation of new technologies; standards and accreditations; renewable technology systems and packaging solutions. This bespoke support is brokered by Invest Northern Ireland technical advisors and delivered by a framework of procured experts across the range of specialisms (Invest Northern Ireland, 2020).

#### 6.5.2.1.4 Scotland

The second Scottish Climate Change Adaptation Programme (SCCAP2) also highlights the finance sector's experience in considering physical risks and suggests learning for other sectors such as forestry. It includes a dedicated section on risks related to access to capital and highlights the SME Loan Fund as relevant to supporting businesses to consider their physical risks to finance. In Scotland

in 2017, the First Minister announced plans to establish a Scottish National Investment Bank, which officially opened in 2020. The aim is to support innovative, high growth firms that have a positive impact in Scotland (Scottish Government, 2020b).

#### 6.5.2.15 Wales

Some recent developments in Wales have triggered a greater focus on resilience as part of the sustainable finance agenda: The Wales Pension Partnership (WPP) that pools assets from eight local government pension schemes announced in July 2020 that climate change represents a material financial risk to its stakeholders and its constituent authorities (the eight local Government pension schemes). The WPP expects its investment manager to ensure that all underlying active managers integrate the consideration of climate-related risks including physical risks into their investment process and to regularly challenge underlying managers to evidence their approach. (WPP, 2020). In addition, the Development Bank for Wales was established in 2017 to support Welsh businesses with loans, equity investment, and seed finance. This replaced many of the functions of Finance Wales £103 million invested directly into Welsh businesses; £76 million additional investment from banks and other private-sector funders; £179 million growth capital injected into the Welsh economy; 457 investments made 3,964 jobs created or safeguarded in Wales (Figures as of 31st March 2020). Climate adaptation is one of the key priorities for the development bank, although generally, their environmental policy seems to be broad and focused on reducing impact. Nevertheless, the approach may provide an opportunity to ensure investment in businesses are factoring in climate risk to their plans in the future. However, the official report 'Prosperity for all: A Climate Conscious Wales (Welsh Government, 2019b) also highlights the risks for businesses from reduced access to capital for their resilience and low-carbon activities, underpinning the need for Government support.

#### 6.5.2.2 Effects of non-government adaptation (B4)

There has been a significant shift in climate analysis and disclosure across the financial sector and other businesses. Worldwide banks and financial institutes have already started performing scenario analysis, and 25% of surveyed UK banks indicate that they are in the process of introducing scenario analysis (Colas et al., 2018). Moreover, the Bank of England identified that the majority of banks are beginning to treat the risks from climate change like other financial risks, but many have yet to begin to measure the risks from climate change comprehensively, including in a range of future scenarios spanning global warming levels of 2°C and 4°C (CCC, 2019). However, whether or not this improved understanding is being translated into adaptation action remains unclear.

There is limited evidence of how companies are using physical risk information and whether this is impacting investment decisions. There is also limited evidence of physical risk considerations leading to capital reallocation in terms of (1) reduced risks through divestments or re-pricing, or (2) through investment into adaptation and resilience. These are supported by findings of Mandel et al (2020). Conversely, with regards to carbon emissions, there is strong evidence that investment companies in particular, including pension funds and banking, are beginning to take climate risks into account and realigning their portfolios. Over 340 investors with nearly \$34 trillion in assets are now asking

companies to report under TCFD (Power et al., 2020). “A survey of 90% of the UK banking sector representing over £11 trillion in assets found that 70% of banks recognise that climate change poses financial risks” (PRA 2018). Credit Ratings Agencies are also starting to incorporate climate risk into their assessments of creditworthiness. (CCC, 2019a).

The increase in disclosure of physical risks through TCFD as mentioned above can be seen as a first step towards adaptation action. Significant progress has been made towards better assessment and disclosure of the physical risks from climate change in the finance sector, mostly driven by FTSE100 companies. However, the initial focus was on a 2°C global temperature rise and not a range up to the 4°C relevant for adaptation risks. The adoption of scenario analysis is expected to influence investment decisions (UNEP-FI, 2019)—exemplified through high market sentiment, with investors and markets signalling a diversion of financial flows as a result of climate change. While expectations may have increased, evidence for the integration of scenario analysis into decision making processes and financial flows is limited (Climate Policy Initiative, 2019). Additionally, the incorporation of physical risk and resilience into investment strategies is growing. For example, the UK FRC’s UK Stewardship Code 2020 integrated climate risks in investment approaches of signatories for the first time (FRC, 2019b). However, this continues to be mostly considered in the context of emission reduction and wider green credentials, with resilience and adaptation only starting to be recognized as material. While clear investment shifts are visible in the context of transition risks like fossil-fuel divestment (Mercer, 2019), physical risks tend not to be considered as material for most investments because of the perception that risk will continue to be insured or because physical risks are only expected to be materialized in the longer-term. It is uncertain whether the true impact of the disclosed actions will occur and can be measured (Deloitte 2020).

In some sectors this long-term view appears to be shifting. Stress testing is being enhanced, but key limitations remain. 4°C degree global warming scenarios are being considered, but it is a work in progress and there is limited evidence that it is leading to adjustments and/or less risk creation. The CCRA2 Evidence Report noted anecdotal evidence that mortgage lenders had started to use insurance industry data and techniques to stress test their portfolios for exposure to extreme weather events (Climatewise, 2015), but this appeared to be more of an exception than a rule. Currently, there is discussion of climate risk at the asset and portfolio level within the real estate sector (ULI, 2019). Whilst there is some evidence of scenario analysis incorporation within commercial real estate (Blackrock, 2019), broader adoption in the real estate market is limited with little or no shift in capital allocation and investment have been noted in terms of physical risks (Carbon Risk Real Estate Monitor, 2019). Moreover, whilst the financial sector is seeing a significant increase in risk analytics and disclosure from a small number of sectoral leaders, think tanks and SMEs that offer climate services, a wide range of methodologies exists, raising questions about accuracy, transparency, and issues from misinterpreting model outputs. This is seen in climate scenarios for stress testing: Assessing a firm’s resilience under different future scenarios is complicated by deep uncertainties around climate change impacts, socioeconomic pathways and technological progress, as well as by the fundamental limitations of currently available modelling techniques (see e.g. Chenet et al., 2019; Stern 2016). It is important that the Bank of England recognises those uncertainties and includes sensitivity analyses of the underlying assumptions and parameters in the biennial exploratory scenario (BES) exercise (GRI, 2020). It is valuable to view this not just as a tool, but a larger organisational learning exercise encompassing multiple sectors.

Although the process is still driven by the largest groups and companies and it is now spreading across other sectors, uptake remains very low across smaller firms. For those firms engaged in climate risk assessments and disclosure this tends to be seen not strategically, but as an immediate obligation to be a responsible company or it is derived in response to regulatory or public pressure. As per Bank of England, only 10% of UK banks said that their approach is strategic, compared to 30% 'responsible' in terms of CSR, and 60% as responsive. Most companies that are implementing the TCFD recommendations expect governance measures to be implemented within less than a year in their businesses. A majority of companies foresee strategy and risk management metrics and targets to be implemented in the next 2-3 years. Complying with the requirements of the Task Force on Climate-related Financial Disclosures (TCFD) creates an incentive for businesses to plan for how they may be impacted by climate change, though this is less likely to influence SMEs, the majority of businesses in England (CCC, 2019).

In our view, there is a disconnect between the current low risk consideration and the high risk of missing adaptation opportunities due to limited investment into resilience and the lack of financial instruments that allow this resilience investment.

Several studies have highlighted the need for insurance in the UK to support physical risk reduction (de Ruiter et. al., 2017; EC 2017; Hudson et.al., 2019; Surminski, 2018). While implementation is still limited, there are some encouraging signs. For example, Flood Re (2020) announced its support of policy holders in their resilience efforts. The Defra Property Flood Resilience FR Roundtable, a cross-industry and cross-sector alliance that includes insurers, has a 5-year plan to promote Property Flood Resilience (PFR) measures and property-level protection measures (PLPMs). These are understood to have a high cost-benefit ratio, potentially reducing property damage by around 75%, reducing financial impacts insurance claims, and limiting disruption to business, schools, and communities (Defra, 2019). These shifts should be closely monitored in the next few years to understand the impact of the pivot towards resilience in the government-supported insurance sector.

With regards to adaptation finance via financial markets there appears to be some innovation in the context of funds for infrastructure and utilities. Some pilot mechanisms like green bonds used by water companies and resilience bonds are being tested. For example in 2017, Anglian Water became the first European utility company to issue a sterling green bond, followed by a second in 2018. The first bond of £250 million will mature in August 2025 and offers a return to investors of 1.625%. The money raised is intended to finance a range of activities, including water abstraction projects, drought and flood resilience schemes, and water recycling projects. So far, Anglian Water has spent £276 million on schemes funded by the green bond, including a wetland restoration project in Norfolk. (Anglian Water, 2020).

### 6.5.2.3 Shortfall in adaptation (B4)

The advances in regulatory action summarised above have led to more disclosure, better governance, and analysis, but these shifts have been limited to large companies and it is unclear how this impacts decision-making and current firm behaviour. Overall, the focus of businesses on adaptation is low compared to mitigation efforts. As per European CFO Survey 2019, only a minority of businesses (249) are reporting adaptation action (Deloitte, 2019). This includes renewing facilities to make them more resistant to extreme weather (14%), purchasing insurance (11%), relocating to



areas less prone to extreme events (2%), reporting risk of climate change (27%), and management and monitoring of climate change in corporate governance processes (25%).

There also appear variation across different sectors regarding adaptation, with some sectors having made significant advances since CCRA2, and others less. Current action is being taken by the government, as evidenced by the Bank of England, PRA, Climate Financial Risk Forum (CFRF), TCFD and UNEP-FI. Scenario analysis is also being adopted by some investors. Additionally, sector specific adaptation is being seen in insurance, banking and investment, with efforts are underway by investors in response to initiatives like the TCFD or UK Stewardship Code. Some companies acknowledge the need for more location-specific information and have announced work to develop a process to produce detailed quantification of physical climate impacts and adaptation measures that can be applied across asset portfolios (Mercer, 2019).

Despite the progress outlined above, there is some evidence indicating an adaptation shortfall. The assessment here highlights several gaps where there is a lack of evidence of action; (1) current lack of quantification of risks, (2) lack in standardisation of risks, and (3) where limited consideration of physical risks when setting investment criteria (for example ‘sustainable real-estate investment’ focuses on climate mitigation issues but does not set out criteria for resilience or adaptation) (Blackrock, 2019). Climate risks are not adequately represented in the market (Black Rock, 2019). There are numerous assumptions being made about climate trends, adaptation and mitigation. Next, risk management can be attributed to investors who are adopting scenario analysis prior to making investments as outlined in UNEP-FI (2019). However, in our view a more active role of investors is required, using these results to be ‘future market makers as opposed to takers’. Investors also have an increasing legal and regulatory obligation to do this (Mercer, 2019). Finally, accounting for adaptation needs to be made more holistic. While exposure and sensitivity of counterparties are commonly assessed, few methodologies include measures of their adaptive capacity to mitigate physical climate risk. Across the four impact channels, methodologies consistently cover a counterparty’s exposure and sensitivity, but there are few methodologies that include its adaptive capacity in their impact assessment. Existing analysis tends to be highly regionally focused (as in ClimateWise with Vivid Economics) or highly aggregated (as in Moody’s Investors Service and Carbone 4). This is due to a lack of available data on the resilience of individual physical assets at the global scale. Increased disclosure as encouraged by the TCFD recommendations could play a vital role in making this data available and corresponding types of assessments possible in the future (UNEPFI 2019a). In addition, an analysis of climate risk screening for companies by the INVEST project finds most of these are based on ‘black box’ tools, that current treatment of financial impacts is limited and rarely specific, and that they have very little robust analysis (RClimINVEST, 2019; de Bruin et al., 2017). Finally, there are concerns around diminishing finance and investment in adaptation post-EU exit due to a governance gap, drawdown of EU financial support, and inability of UK firms and to access EU research funding streams such as Horizon Europe (Acclimatise, 2020). In terms of financing adaptation and resilience it is unclear how EU exit will impact existing mechanisms such as the Green Climate Fund and the subsequent impact on the private sector as a result.

Overall, there is medium confidence of the adaptation shortfall. This is because some existing measures taken by firms may not be specifically classified under adaptation. There is a possibility that many existing corporate actions to address this risk, such as standard risk management planning, may not be explicitly classified under adaptation efforts (Frey et al, 2015).

#### 6.5.2.4 What are the barriers preventing adaptation to the risk? (B4)

Perhaps the largest barrier to current action on adaptation continues to be the perception of adaptation as a long-term ambition, where the material impacts of physical risk expected are long-term. Many businesses – especially SMEs - do not understand the risks and more importantly do not know what risks they need to be assessing. To illustrate, only 52% of the surveyed businesses reported that climate change risk is discussed at the Board-level in their organisation, as per the CCRA3 Business Survey. Subsequently, climate risks are not priced in and markets remain “blissfully ignorant” (Black Rock 2019) regarding assumptions about climate trends/adaptation/mitigation. As per the CCRA2 Evidence Report, there is evidence that some companies experience difficulties in accessing finance for implementing their own adaptation and resilience measures. The water, energy, airports, rail and telecommunications sectors can be susceptible to regulatory restrictions that prevent investments in resilience to varying degrees. This corroborates with recent CDP 2018 Business Survey results (CDP, 2018). Beyond the lack of funds, businesses face a number of challenges in integrating adaptation to operations and future planning:

- The majority of financial institutions indicate that climate risks are not captured in the credit-rating process (Marsh & McLennan Companies. 2018) and uptake of tools is low. Moreover, businesses may not have the right data or infrastructure in place to monitor and mitigate climate risks using scenario analysis. Businesses may also not have the right level of skills, training or in-house capabilities to interpret the climate scenarios generated.
- There are many challenges to integrating long-term forecasts and scenario analysis into business planning which leads to discrepancy in the timescales adopted in finance and climate-modelling (Frey et al, 2015). For instance, risks may only be considered at critical points such as making investment decisions.
- There is a lack of incentives for adaptation action in companies’ performance management systems, for example, very few have resilience-based teams and management indicators (Frey et al, 2015).
- There are risks of moral hazard. Reduced access to finance is not assumed to be a business threat given perceived government intervention to fill financing gaps (Frey et al, 2015). A similar moral hazard exists in the assumption of insurance availability.
- Businesses are not rewarded for early action, for instance incorporation of climate risk exposure is not reflected in many insurance rates, discouraging firms from further undertaking this (Frey et al, 2015).
- There remains lack of engagement from infrastructural investors despite top-down policies to support sustainable infrastructure (Marsh & McLennan Companies 2018).
- The risk analysis currently only captures direct impacts, and not the indirect ones. For instance, there are reasons to believe that physical risk will impact economic growth and GDP (and transition risk in some geographies), which in return would cause indirect impacts on real estate investments. Moreover, the indirect impacts related to supply chain are also not included in the model as of today (UNEP-FI 2019).
- Different sectors may have varying capabilities given time-horizons of investments. For instance, according to a survey cited in the Our Future in the Land Report (Farming and Countryside Commission, 2020), most farmers are planning 2-5 years ahead, with >50% flexibility in planning

in the five-year time horizon. This time horizon may act as a barrier in accessing innovative finance required in the sector (RSA 2019). Whilst larger players such as Unilever and Nestle (Landworkers' Alliance, 2019) are using scenario analysis to assess longer-term climate risks, small agricultural business usually don't.

Stakeholder discussions during the workshops carried out to support CCRA3 show that companies find it easier to manage carbon emissions than identifying and measuring adaptation action. Recognizing adaptation as a continuous process that needs to be adjusted and developed rather than a one-off exercise requires a different strategy and approach within a company. Adaptation needs and risk profiles are different for each business so establishing what adaptation metrics and information can help with business decisions is very company- and sector specific. While there are a growing number of sources of information to measure risk and adaptation, there is no clear metric to assess the level of adaptation at company or location level, as one metric is not a realistic goal for adaptation. This has become a key issue, also in the application of scenarios and risk assessments for financial decisions. There are a variety of standards, tools, indices, and other assessment mechanisms that aim to address this issue, but no singular assessment is utilized, and the information is often qualitative, self-reported and not consistently validated. In the UK, several companies are currently exploring this challenge under the UN's ARISE initiative and the Bank of England has also asked for further clarity on this to support climate stress testing and climate scenario analysis. CCC (2019a) also expands on these barriers:

- While many large businesses have expressed support for the TCFD, this has not yet led to better assessment and planning for climate change risks and the current guidance does not require the consideration of higher climate change scenarios.
- Many businesses still do not have basic continuity plans for extreme weather, and there are no indicators available that help to show whether vulnerability and exposure is increasing or decreasing.
- Complying with the TCFD recommendations will lead to more useful information being reported and create incentives for businesses to assess how they may be impacted. However, the current guidance does not encourage consideration of higher climate change scenarios (up to 4°C global warming) and the voluntary approach is unlikely to be strong enough.
- The Government's Industrial Strategy makes no mention of climate change as a risk to meeting its goals, nor as an opportunity for UK skills, services, and technologies to support adaptation efforts. Some action by businesses is underway to address the risks and take advantage of opportunities from climate change, but significant gaps remain in considering the risks to trade, international flows of finance and the need for new skills, for example in the housing and infrastructure sectors.
- While many large UK organisations have expressed support for the TCFD, it is not yet clear that this is necessarily leading to alignment with the recommendations and better assessment and planning for climate risks.
- The adoption of climate modelling and consideration of climate risks in investor decision-making will have significant knock-on effects, encouraging firms to reconsider their own adaptation strategies but the financial sector currently has limited the tools to incorporate level of adaptation into decision-making.

The financial sector has the incentives to remove some of these barriers without Government intervention. For example, mechanisms to partially alleviate asymmetric information issues can be addressed, and information on credit and insurance products can be made more easily accessible to businesses. Pricing (credit interest rates and premiums) could better reflect externalities to create the appropriate incentives for businesses to adapt. However, in the future the industry might respond to rising risks and liquidity issues by finding new ways to re-insure risks through alternative risk transfer markets, by raising premiums, or by withdrawing from the market. Government intervention is therefore needed to ensure the financial and insurance markets are provided with the appropriate information and regulatory framework which would ensure they can continue to provide access to capital and insurance to help people increase their adaptive capacity and resilience to climate risks. In particular, the Government role would be the development of climate models and information sharing of risk data, regulation, protecting the most vulnerable, managing moral hazard and implicit liabilities, and ensure policy coherence between different sectoral policies (Cimato and Mullan, 2010).

#### 6.5.2.5 Adaptation scores (B4)

**Table 6.17:** Adaptation scores for risks to finance, investment and insurance including access to capital for business.

Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)

### 6.5.3 Benefits of further adaptation action in the next five years (B4)

#### 6.5.3.1 Additional planned adaptation that would address the adaptation shortfall? (B4)

There have been significant shifts in assessing, disclosing and analysing climate risks and more is expected in light of expected shifts from voluntary to mandatory action driven by regulators. However, translating this increased risk knowledge into action and drawing conclusions is equally important, and the extent to which companies will successfully do this remains unclear. While it is clear that the extent of physical risks is currently low and expected to become significant in the longer-term there are clear dangers in considering physical risks ‘as under control’: lock-ins for example in terms of real-estate investment but also lack of insurance uptake, particularly on business continuity.

Since CCRA2, changes have mainly been made in climate risk regulation and reporting as opposed to changing capital flows. Moreover, given the tightening climate policy landscape, there are significant lock-in effects if there is no substantial redirection of financial flows. Whilst banking and insurance sectors have effectively responded to current extreme weather events, the increase in magnitude and frequency of impacts in the future means the likelihood of “unhedgeable risk” is higher – straining the insurance sector. Given that financial risks are still not integrated within firm operating

models or in financial markets as a whole, there are still significant systemic risks (Mandel et al, 2020). Whilst companies have started adopting TCFD recommendations, identifying climate risks is only the first step. TCFD's most recent status update report acknowledges that there needs to be a better understanding of how disclosing climate-related financial information is changing corporate strategies on adaptation, and how investors are using the disclosed information to inform their decisions (Power et.al. 2020; TCFD, 2020). CISL (2019) recommends early action in addressing risks to accessing finance and investment is predicted to lead to higher economic growth rates and returns over the long run when compared to scenarios of inaction. Moreover, further investment is required to scale-up pre-existing resilience solutions and technologies (NDF, 2020).

The following are a number of key areas that could be addressed in the next five years:

- Requirements imposed on banks and insurers: Based on Pillar 2 of the supervision of institutions' risk management, regulators could prescribe additional capital on a case-by-case basis, for instance if a financial institution does not adequately monitor and manage climate-related risks. This would first require new expectations to be set in this regard (BIS, 2020). Further action is required by banks in order to meet Bank of England stress testing requirements. Currently there is very little data and organisational capacity to collect information in the aftermath of disasters (e.g. collection strategies after a flood) (Deloitte, 2020). Banks require data (e.g. location of collateral, exposure to carbon intensive industries etc.) in order to better respond to physical and transition risk. For instance, green vs brown exposure and funding of carbon intensive industries is not being considered (Deloitte, 2020). In scenario analysis, the banking sector needs to adopt and consider much longer timelines than it is used to at present (Deloitte, 2020).
- Broadening scope of existing regulations: The current review of climate stress testing by the Bank of England's PRA (Bank of England, 2019) provides an opportunity to broaden the scope, identify limitations and important constraints, and support companies in their internal interpretation of scenario analysis results. Whilst the stress-testing is intermittently paused due to COVID-19 (IMF, 2020), this could be a step towards encouraging more scenario-based analysis among financial institutions on a regular basis. In the future, regulators could make it mandatory for financial institutions to stress-test their portfolios against a common set of scenarios. (UNEP-FI / Vivid 2019). Mandatory disclosure is also called for by the IMF (2020). Stakeholder engagement suggested there is insurers support for this, with mandatory disclosure of methodologies and impact recommended.
- Insurability: Given rising uncertainty, McKinsey (2020) recommend risk-sharing agreements between private and public financial institutions, similar to that seen in flood insurance, in order to meet financing gaps. Given that Flood Re is only available to non-businesses, there should be increased incentives for resilience to businesses. This also directly relates to uptake of insurance. Whilst there is an increase in the uptake of climate related insurance products, products need to be more streamlined, made cost-effective and user-friendly to promote further business uptake (Marsh & McLennan Companies 2018). Insurance can be used to incentivise risk-reducing behaviour, for example by rewarding adaptation measures like hardening of physical assets (McKinsey, 2020). As highlighted in section 7.10 of Chapter 7 (Challinor and Benton, 2021), this

uptake in insurance from the UK's expertise within re-insurance companies and catastrophe risk modelling organisations is an opportunity for the UK insurance market to grow.

- **Disclosing and reporting:** Further standardisation and clarification on scenario analysis models are required so comparisons can be made. Moreover, inclusion of additional asset classes will make these models more useful for investors (Mercer, 2019). Standardisation can occur through investor collaboration facilitated by government-led initiatives (UNEP-FI, 2019). Scenario analyses currently do not cover the entire value-chain of businesses and further integration is required between transition and physical risks as well as the link between micro and macroeconomic impacts (UNEP-FI, 2019). Further developments of dashboards and monitoring mechanisms are required to capture “investors and markets channelling finance to climate solutions” and change in financial flows are a response to climate risk (CPI, 2019). Additionally, more bottom-up information, such as KPIs from businesses, need to be incorporated in scenario analyses which have predominantly been top-down. A push for disclosure of granular, asset level data is required from businesses for scenario analysis to be successful (UNEP-FI, 2019).
- **Financial and physical risk metrics:** It is important to recognise the interplay of financial metrics and physical risk metrics: for example, the credit risk of a bank from increasing physical risk can be low if it does not lend to companies in high-risk areas. Finity (2019) show it is important to distinguish between risk to individual financial companies versus wider financial implications. Unless physical risk is being reduced through more adaptation investment and action, those damages will occur and have financial implications.
- **Incorporating risk reduction and data into insurance requirements:** One proposed solution relating to the short-term valuation cycle issue is that policymakers and insurers could incorporate risk reduction and adaptation measures into insurance requirements (CISL, 2019). Other options include making sure risk data is populated across a wide range of sectors and groups, including a focus both on the current symptoms and problems and the underlying causes incorporated into day-to-day decision-making. Surminski (2017) showed that it is essential to first address the use of data and transparency around risk levels. This foundational trust and understanding is needed to reduce the risk of the private sector withdrawing altogether from the flood insurance space or consumers not being able or willing to pay high premiums (Surminski, 2017).
- **Financing adaptation:** Where funding pools exist, like bond markets, better education is required to match counterparties (Marsh & McLennan Companies 2018). Further research is required in the area of new products, such as resilience bonds, which would use premium discounts for long-term planning, such as investment in sustainable infrastructure, in the catastrophe bond market. Synergies between climate financing and risk management strategies in the banking and insurance sector must be further explored (Marsh & McLennan Companies 2018).
- **More collaboration between different parts of the financial system:** Capital providers to investors and lenders will likely want to understand how such location decisions, intermediated by insurance availability (discussed above) and adaptation action (discussed below), are taking account of the physical risks of climate change. To the extent that investors and lenders do alter

location decisions, it is projected to be much less disruptive to the real economy if this happens over a long period of time rather than as an abrupt response to one or a series of particular events (CISL, 2019). However, investors and lenders, combined with policymakers, may find it easier to take a longer-term perspective. They could work in concert with insurers to encourage the uptake of adaptation measures, for instance, by making both loans and insurance contingent on the installation of relevant adaptation measures (CISL, 2019). This is in line with UNEP-FI (2018) who encourage improved collaboration between banks, borrowers, governments and the insurance industry, and would increase the quality of forward-looking disclosures.

#### 6.5.3.2 Indicative costs and benefits of additional adaptation (B4)

It is difficult to estimate the potential costs and benefits of adaptation. However, what is clear is that the potential risks to the financial markets from climate change are extremely large, and because of the role of UK financial services, very large for the UK. EIU (2015) estimated the value at risk, as a result of climate change, to the total global stock of manageable assets (currently \$143 trillion) as \$4.2 trillion (mean expected losses, discounted in present value terms) between now and the end of the century, and still half this even under a pathway to 2°C global warming by 2100.

#### 6.5.3.3 Overall urgency score (B4)

<b>Table 6.18</b> Urgency scores for risks to finance, investment and insurance including access to capital for business.				
	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency Score</b>	Sustain current action	Sustain current action	Sustain current action	Sustain current action
<b>Confidence</b>	Medium	Medium	Medium	Medium

Note: The 'sustain current action' score is based on understanding of the current magnitude and the emergence of regulatory and corporate activities to increase the resilience of the financial sector. However, given the medium and high future magnitude scores this urgency score needs to be watched and if necessary revised to 'more action needed' should the current activities not lead to tangible changes in exposure and vulnerability of the sector. Monitoring if and how the above barriers and gaps are addressed will be important. It is expected that businesses will be impacted by changes to cost of capital, as measures taken by banks, investors or insurers to reduce climate risk exposure are expected to come at a cost to those at risk who require capital. Similarly, there is potential for systemic risk due to lock-ins via risk-insensitive investment decisions and overreliance on insurance, which may become a less viable adaptation option in the future if climate risks start to become 'unhedgeable'.

#### 6.5.4 Looking ahead (B4)

This section has explored a range of topics under one heading, which is understandable as the issues covered are interconnected. However, given the growing prominence and evidence base it might be

advisable to separate out the four specific risks (insurance, investments, costs of capital, finance for resilience) for UKCCRA4. Similarly it is important to conduct further research on the interplay between direct physical and indirect financial risks from climate change and also consider the interdependencies between transition, liability and physical risks. As outlined by Bowen et.al. (2020) “physical and transition risks tend to be assessed separately, given the complexity involved in modelling and quantifying each case, (...) but it is important to avoid investors focusing on ‘transition risks’ and insurers on ‘physical risks’, given that physical risks are also important for investments, while insurance decisions are also important for transition risks as well as for liability risks including litigation.” (Bowen et.al. 2020). This will also require methodological amendments to CCRA4, for example a joint investigation of physical and transition risks and how they interact. The Government’s recently announced centre for Climate and Environmental Risk Analytics (CERAF) could help facilitate this (University of Oxford 2021). Similarly there will need to be more engagement between the finance sector and its clients as well as regulators to ensure that advances in climate analytics are transparent and correctly interpreted for day-to-day decisions.

## 6.6 Risks to business from reduced employee productivity due to infrastructure disruption and higher temperatures in working environments (B5)

Employee productivity in this section encompasses work output, as opposed to labour productivity which refers more to workplace efficiency - output per worker, per job and per hour. A changing climate (average temperatures) has the potential to affect productivity, potentially both negatively and positively, as well as indirect impacts as a result of infrastructure disruption (Chapter 4: Jaroszweski, Wood and Chapman, 2021) and higher temperatures in working environments. There are also risks associated with changing extremes, particular high temperatures, which can have negative impacts on employees’ health and wellbeing (Chapter 5: Kovats and Brisley, 2021) and their ability to commute to work. There is some evidence that businesses are experiencing these impacts already. The risks are likely to vary widely across business sectors and geographies, with a range of factors determining risk levels, such as the type of work (e.g. construction or industrial processes), whether it takes place indoors or outdoors, and the local built environment and infrastructure (e.g. passive ventilation). The COVID-19-related shift to home-working is likely to offer insights on overall productivity drivers but does also create a new risk, particularly for those employees working from homes prone to overheating. There are no specific studies which examine the differences between England and the other Devolved Administrations.



## 6.6.1 Current and future level of risk (B5)

Note: it has not been possible to split the evidence by UK country for this risk.

### 6.6.1.1 Current risk (B5)

#### 6.6.1.1.1 Current risk - UK wide

Heat and humidity impact employee productivity (Kjellstrom et al., 2009; Kjellstrom et al., 2014). In order to cope with heat, there is typically a reduction in work intensity or an increase in breaks. This occurs through self-pacing which results in lower employee output. These reductions in work intensity can translate through into labour productivity, which is an aggregate measure of output per employee or unit of labour. Labour productivity measures the volume of gross value added (GVA) produced per unit of labour input, with hours worked as the preferred labour input (NAO, 2020). In extreme heat, there are also risks of heat stress, heat exhaustion, heat stroke and even fatality. These effects apply to outdoor workers in particular, but also to indoor workers who are not in a temperature-controlled environment.

Extreme weather events, such as heat waves, can also impact productivity by denying workers access to their work sites, preventing them from, or impairing their ability to work remotely, or causing them to have to take leave to deal with problems at home caused by extreme weather. As described in the CCRA2 Evidence Report and outlined in the National Business Resilience Planning framework, severe weather that causes transport disruption and other infrastructure failure also leads to staff absence (Cabinet Office, 2014; Trade Union Congress, 2009). See also Chapter 4 (Jaroszweski, Wood and Chapman, 2021) for infrastructure disruptions. The LSE Climate Risk Business Survey (2020) shows that businesses are already impacted by reduction in labour productivity due to heatwaves and due to physical damages to infrastructure – with respondents in England significantly more impacted than those located in Wales, Northern Ireland or Scotland.

A limited number of studies have considered the impacts of higher temperatures on productivity in the UK, meaning there is therefore considerable uncertainty about the magnitude of impacts. There is also considerable uncertainty in the results of these studies, and the degree of the risk to the UK. Importantly the risk is not evenly spread, and varies between geographical locations, indoor and outdoor workers (Trade Union Congress, 2009) and across workers engaged in particular sectors or occupations. For example, heavy outdoor manual labour or maintenance employees (e.g. in telecommunications, IT and those working on industrial infrastructure such as oil refineries, chemical and petrochemical plants, gas processing plants) working outdoors, are likely to be at greatest risk of heat stress, dehydration, UV radiation and potentially skin cancer, though overheating indoors will also impact employee productivity from other sectors. Workers engaged in particular occupations, for example heavy outdoor manual labour, are likely to be at the greatest risk of heat stress. Recent evidence from the social care sector points to detrimental impact of heat on staff wellbeing: In a case-study of both an older and a modern care home in London (Gupta and Howard., 2020) it was reported that staff found the summertime thermal conditions more uncomfortable than the residents did.

Our UKCCRA3 stakeholder engagement revealed some anecdotal reports of labour productivity being impacted by other climate-related variables, notably rain, wind, snow and cold temperatures, which can affect productivity because of the need to withdraw work due to accident risks, for example in sectors such as construction or transport. However, evidence is limited and no assessments exists.

#### 6.6.1.1.2 Current risk - England

No evidence is available for England.

#### 6.6.1.1.3 Current risk - Northern Ireland

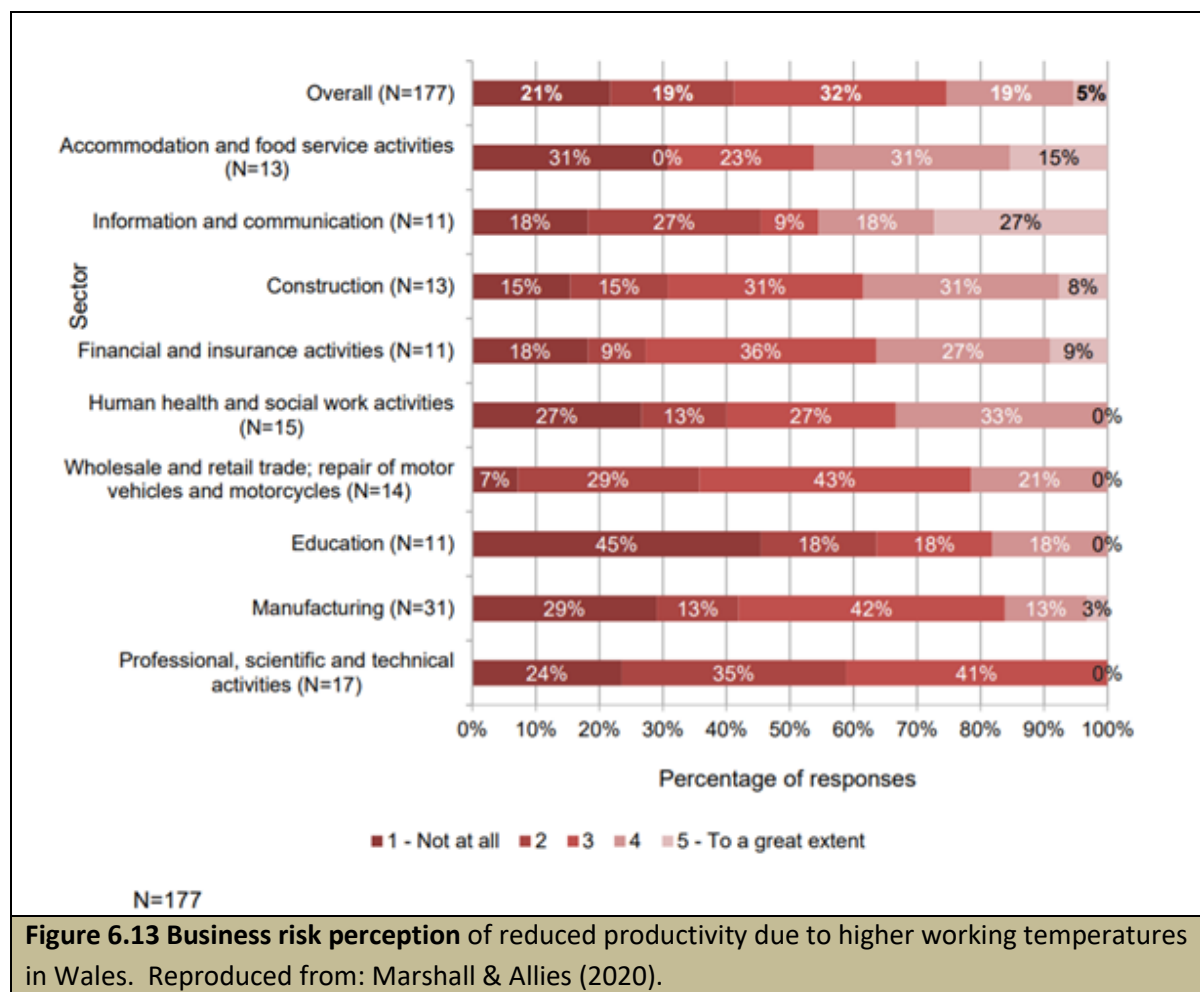
No evidence is available for Northern Ireland.

#### 6.6.1.1.4 Current risk - Scotland

Anecdotal evidence collected during stakeholder discussions conducted as part of the CCRA3 engagement with adaptation experts in Scotland suggests that heat resilience of the workforce, particularly in agri-businesses and process related sectors is lower than of those working in commercial buildings mainly due to existing building regulations for offices in Scotland.

#### 6.6.1.1.5 Current risk - Wales

As shown in Figure 6.13, the Welsh Government's business survey (Marshall & Allies, 2020) indicates 21% of respondents do not at all think their business is at risk of reduced productivity due to higher working temperatures. 70% of respondents fall somewhere in the middle of the scale. Only 5% of respondents believe their business is at risk to a great extent.



#### 6.6.1.2 Future risk (B5)

A key measure of the effect of temperature on humans is known as the Wet Bulb Globe Temperature or WBGT (Lemke and Kjellstrom, 2012), which is used in international and national standards to specify workplace heat stress risks. However, no aggregate analysis is available for WBGT across the UK, and there is only limited evidence on future risks to labour productivity in the UK. Past events in the UK suggest extreme outdoor temperatures can have significant effects on production. This was reported in CCRA1 (Baglee et al. 2012) which suggested potential impacts for indoor work (in the absence of additional air conditioning uptake) that were very large. More recently a study by Lloyd et al (2016) estimated the loss of productivity (days lost) from climate change. For the UK, the values were relatively low when compared to southern regions of Europe, and especially to Asia, where these losses could be very high. These findings are supported by Gosling et al. (2018). However, it is difficult to establish a temperature threshold at which productivity starts to decline. Costa et al. (2016) found that a stabilisation trajectory of a 2°C increase by 2100 would represent a medium<sup>11</sup> risk for businesses due to the decline in employee productivity (high for England, low in the other three countries) in 2080, while an increase of 4°C by 2100 would represent a high risk across the UK (Costa et al., 2016). Costa et al (2016) also assess this

<sup>11</sup> The magnitude rating applied by Costa et al. 2016 is different from the CCRA3 magnitude rating outlined in Chapter 2 and underpinning the urgency scores in this chapter.

in terms of impact on city economies. They find that total losses to the urban economy could range between 0.4% of Gross Value Added (GVA) for London in a warm year in the far future (2081-2100), with a specific focus on impacts in the financial sector.

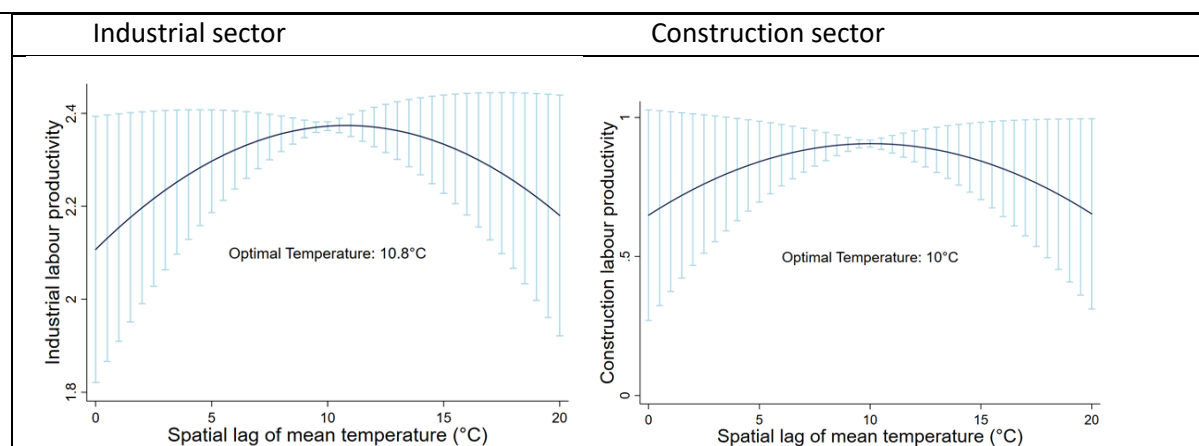
Results from the EU-funded COACCH research project (Schleypen et al., 2019) suggest that for industrial and construction sectors, the UK is likely to be less impacted than many other areas of Europe, under a RCP8.5 scenario (see Box 6.4).

**Box 6.4** Impact of temperature increase on labour productivity in the EU: evidence from the COACCH Project (Interim Results).

The European Union funded COACCH (Co-designing the Assessment of Climate Change costs) project assesses the economic cost of climate change in Europe (Schleypen et al., 2019). The results found gradual changes in temperature and extreme heat events have significant negative direct impacts of on both industrial and construction labour productivity. They report a non-linear relationship between outdoor temperature and labour productivity in industry and construction sectors. Productivity decreases below and above thresholds, and thus depending on the baseline climate, further increases in temperature can result in a negative impact.

In the agricultural sector, future climate change was estimated to affect labour productivity for the EU by 2% under RCP2.6, 4.2% under RCP4.5, 5% under RCP6.0, and 6.3% under unmitigated climate change scenario of RCP8.5 by 2070. In the industrial sector, these impacts are expected to be 1.3% (RCP2.6), 2.5% (RCP4.5), 3% (RCP6.0), and 4.5% (RCP8.5), respectively. For the UK, productivity losses were estimated to be between 1% (RCP2.6) and 5% (RCP8.5) by 2070.

The optimal temperature for the services sectors is higher, as workers are not as exposed to outside temperatures, noting also that higher temperatures benefit the attractiveness of certain sectors, such as summer tourism. However, the study did not pick up large statistically significant effects on the services sector.



**Box 6.4 Figure 1** Relationship between mean temperature and productivity. Reproduced from Schleypen *et al.* (2019).

Whilst studies at the UK level are sparse, there is evidence of heat risk impact on employee productivity on a global and regional scale (ILO, 2019; Kjellstrom et al., 2016) that may also be informative for the UK and has the potential to impact UK businesses through supply chains. The associated social and economic impacts of heat risk could be considerable. In a scenario of approximately 5°C global warming at the end of the century<sup>12</sup>, global gross domestic product (GDP) losses are projected to be greater than 20% by 2100 (Kjellstrom et al., 2016). While this is more extreme than the scenarios considered here for the magnitude scoring, it can be inferred that a scenario of 4°C global warming at the end of the century would also lead to substantial impacts on GDP. Environmental heat stress is likely to have reduced labour capacity by 10% in peak months over the past few decades and is projected to reduce labour capacity to 80% in peak months by 2050 (Dunne et al., 2013). In a scenario of approximately 4°C global warming at the end of the century<sup>13</sup>, labour capacity could reduce to less than 40% by 2100 in peak months globally, with most tropical and mid-latitudes experiencing extreme climatological heat stress.

Decline in employee productivity may also be cumulative, depending on the number of days off work or frequency and duration of commute delays. The magnitude of the risks associated with heat may also be higher than expected due to under-reporting of heat related illnesses (Xiang et al., 2016).

### 6.6.1.3 Lock-in and thresholds (B5)

#### 6.6.1.3.1 Are there lock-in risks?

Business decisions today about design and operation of office buildings or operational sites and manufacturing processes have high capital expenditure and will determine future risk levels. Examples are choice of material, building type and office set-up when refurbishing or building new. The performance of these under heat stress is an important factor for productivity. See Chapter 5 (Kovats and Brisley 2021) on the built environment.

For many businesses air conditioning is the main solution to heat stress impacting indoor workplaces, as Deschênes and Greenstone (2011) highlight. However, Power et al (2020) identify various drawbacks to this coping strategy. First, air conditioners place increased stress on electricity networks, which may already be experiencing stress due to high temperatures and peak demand, though this has not been historically an issue for the UK, where the grid is sized for the winter peak, However this may change: see Chapter 5, risk H6 (Kovats and Brisley, 2021). Secondly, air conditioners contribute to greenhouse gas emissions and air pollution emissions through their use of electricity (when generated with fossil fuels- see Net Zero section below). Though decarbonisation and efficiency gains arising from the shift to Net Zero will actually remove these emissions, some warming impact will still remain due to the fact that they involve the use of refrigerants with high Global Warming Potential which result in direct GHG emissions through leakage (Dreyfus et al., 2020). Finally, air conditioners generate waste heat during operation that compounds heatwave

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<sup>12</sup> With the HadGEM2-ES climate model driven by the RCP8.5 concentration pathway, see Betts et al. (2015)

<sup>13</sup> With the ESM2M climate model driven by the RCP8.5 concentration pathway. ESM2M has a medium climate sensitivity whereas HadGEM2-ES has a relatively high climate sensitivity, so ESM2M warms slower than HadGEM2-ES with the same concentration pathway.

conditions (Salamanca et al., 2014). It is, however, possible that more energy-efficient air conditioning technology will be developed in the coming years (IEA, 2018) and that waste heat will be captured and resupplied to support hot water and heating demand (CIBSE Journal, 2020). Also, cooling demand could be met through reversible heat pumps, particularly in public and commercial buildings with mechanical ventilation. A large number of these units are already in use (though exact estimates vary) - their prevalence is expected to grow as part of the shift off fossil fuels (stakeholder discussion). The implications of a COVID-19-induced trend to working from home for overheating and cooling are not yet clear and should be monitored, particularly in terms of labour productivity and heat stress as most home offices do not have air conditioning.

#### 6.6.1.3.2 Are there potential thresholds?

The literature suggests thresholds associated with levels of work output for different types of indoor and outdoor work, for example in the construction industry, in service sectors and tourism (Schleypen et al., 2019). This corroborates with other findings for outdoor tourism facilities, which may become unsafe due to heat and Ultraviolet (UV) exposure after a certain temperature (CEU, 2019a). This indicates there are also likely to be associated thresholds for other sectors and industries, which involve high temperature environments, such as some food production and manufacturing. Some of these thresholds are set down in policy, in the form of occupational health standards and temperature limits (see adaptation section). Observed behaviour amongst populations also highlights that there may be biophysical/policy thresholds – e.g. when temperatures reach a point such that there is social consensus or trade union intervention, and staff need to be sent home. Another threshold relates to natural capital and cooling effect provided, particularly in urban areas: Irreversible natural capital loss poses a threshold for these heat-reduction benefits (UK Centre for Ecology and Hydrology 2020).

#### 6.6.1.4 Cross-cutting risks and inter-dependencies (B5)

There are interacting risks with infrastructure disruption and the built environment which includes risks of overheating in homes and in non-domestic buildings (discussed in Chapter 4: Jaroszweski, Wood and Chapman, 2021). There may also be cascading risks due to infrastructure disruptions arising from extreme weather events. For example, overheating of electricity substations may also compound risks from higher temperatures in working environments (IEMA, 2013) by disrupting availability of air conditioning, in turn further exacerbating risk to employee productivity. In addition, reduced employee productivity reduces overall health and wellbeing (discussed in Chapter 5: Kovats and Brisley, 2021).

#### 6.6.1.5 Implications of Net Zero (B5)

There appear to be synergies as well as trade-offs between Net Zero and adaptation efforts in response to heat. First, changing temperature patterns will affect the energy demand of businesses. There will be higher energy demand from cooling, to the extent that air conditioning, rather than building designs and behavioural measures might be used to manage the impacts of higher temperatures (see Chapter 5: Kovats and Brisley, 2021). The greater uptake of air conditioning in commercial premises could pose challenges for a decarbonised power system in the summer, although the demand peak in the hot midday hours also coincides with peak sunshine and therefore

solar production. Second, some air conditioning devices also use high Global Warming Potential (GWP) refrigerants, which could result in increased greenhouse gas emissions through leakage.

Conversely, there may be less demand for spatial heating in winter, creating some benefits in the hard-to-decarbonise heating sector (see risk H6, Chapter 5: Kovats and Brisley, 2021).

The second synergy or trade off relates to waste heat from air conditioning and urban heat island effects, where a feedback loop exists. As temperatures rise, and are exacerbated by urban heat island effects, there is the potential for greater air conditioning to be employed, with waste heat further contributing to higher temperatures in urban heat island effects. Conversely, there may be some synergies, with the potential for such heat to be captured and used for space and hot water heating. However, there is limited research on this issue, and it warrants further investigation.

#### 6.6.1.6 Magnitude scores (B5)

**Table 6.19** Magnitude scores for risks to business from reduced employee productivity due to infrastructure disruption and higher temperatures in working environments.

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
England	Low	Medium	Medium	Medium	High
	(Medium confidence)	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Northern Ireland	Low	Low	Low	Medium	High
	(Medium confidence)	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Scotland	Low	Low	Low	Medium	High
	(Medium confidence)	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)
Wales	Low	Low	Low	Medium	High
	(Medium confidence)	(Medium confidence)	(Low confidence)	(Low confidence)	(Low confidence)

The magnitude scoring (Table 6.19) is based on expert judgement, as quantified estimates of risk are not available. In net terms, i.e. sum of positive and negative, we deem the current risk to be low across the country, with annual economic damages less than £10 million in England and less than £1 million in the rest of the country. Future risks are low, medium to high depending on sectors and

geographies and temperature pathway. For England the 2050s projections are higher than for the rest of the country due to higher temperature projections, with economic damages going into the £hundreds of millions. Studies indicate a possible 2% reduction in labour productivity by 2100, which is a significant figure.

## 6.6.2 Extent to which the current adaptation will manage the risk or opportunity (B5)

### 6.6.2.1 Effects of current adaptation policy and commitments on current and future risks (B5)

#### 6.6.2.1.1 UK-wide

The productivity of the UK's workforce depends on a range of different factors but is 16% below the other 6 of the G7 economies (ONS, 2018), and closing this gap remains a priority for the UK, as set out in the Industrial Strategy (BEIS, 2018). Globally, early guidance is beginning to emerge on the strategies that can be employed to manage future risks of heat to productivity. The EU Heat Shield project has explored the impact of heat on productivity across Europe, and developed a series of guidelines and resources to mitigate heat stress in the tourism, transport, manufacturing, construction and agriculture sectors, as well as the development and roll out of a personalised alert service (Morris et al., 2019). However, despite the availability of resources, there is limited impact of this work being translated into domestic policy (Morabito et al., 2019).

Across the UK, there are existing Health, Safety and Welfare Regulations that also cover temperature in indoor workplaces, such as the Workplace (Health, Safety and Welfare) Regulations 1992 and the Management of Health and Safety at Work Regulations 1999. These apply to most workplaces except those involving work on construction sites, those in or on a ship, or those below ground at a mine. These require employers to address temperatures that are uncomfortably high, by taking all reasonable steps to achieve a reasonably comfortable temperature (though note that what these temperatures are is not defined and left to individual discretion). Examples of actions include insulating hot plants or pipes, providing air-cooling plants, shading windows and siting workstations away from places subject to radiant heat. If a reasonably comfortable temperature cannot be achieved throughout a workroom, local heating or cooling (as appropriate) should be provided if it cannot be achieved through lower carbon interventions such as increased use of shade and natural ventilation, use of insulation, or relaxation of workplace dress codes. In extremely hot weather, fans and increased ventilation may be used instead of local cooling. The Health and Safety Executive (HSE) provides guidance on temperatures, as well as heat stress and thermal comfort including the provision of a Heat Stress Checklist for businesses.

#### 6.6.2.1.2 England

In England, the National Health Service (NHS) Outcomes Framework and Heatwave Plan include specific outcomes to reduce summer deaths and illness, but these have not yet fed through into other policies related to overheating, including for businesses. The updated National Planning Policy Framework includes a requirement to consider risks from overheating in new developments but has also removed support for energy efficiency improvements to buildings. In terms of sectors, there is



evidence that labour productivity will impact heritage organisations, particularly those that undertake fieldwork such as archaeological organisations and businesses and building conservation, as per Historic England.

### 6.6.2.1.3 Scotland

In Scotland, support to businesses is provided by Adaptation Scotland programme, whose guide 'Climate Ready Business' provides tools and resources to businesses to adapt, although heat is not included as a major factor for consideration. And there is emerging evidence of some sectoral responses. In Scotland, the Cultural Adaptations project, led by Creative Carbon Scotland is working to develop bespoke tools and support for the Cultural Sector to manage a wide range of climate risks, and is working to pilot it across cities in Europe (Creative Adaptation Scotland, 2018). Realising adaptation opportunities also depends on the support of trade unions and their ability to realise this is a thermal comfort issue. As per the Power et al, (2020) study, the most widespread activities employed by businesses are temporarily decreasing activity as a coping mechanism for extreme heat. Other very or moderately common approaches include keeping windows open at night, using personal fans at work, drawing curtains, providing protective clothing or sunscreen, changing routines (e.g. changing work hours to be out of the heat of the day) and installing air conditioning units.

### 6.6.2.1.4 Wales

The Welsh Government has a Climate Risk Business Tool as highlighted in Section 6.3, enabling businesses to go through likely risks and their management, including high temperatures and infrastructural disruption (Welsh Government, 2016). In 2020 the Welsh Government commissioned a survey of Welsh Businesses to identify how best to support them to adapt to higher working temperatures and infrastructure disruption as a result of climate change. 243 SMEs responded via survey and interview. Key findings are that most business don't see climate risk as a pressing issue, that they are unclear on the risks, that few are taking action and they have insufficient information. Generally speaking, the research showed that Welsh Businesses didn't differentiate either higher working temperatures or infrastructure disruption (from flooding or otherwise) as climate risks. As committed in its adaptation plan, Prosperity for All: A Climate Conscious Wales (Welsh Government, 2019b), the Welsh Government plan to take recommendations from the report to develop guidance and support to businesses, focussing on provision of appropriately framed information and work with early adopters from the target group (Marshall & Allies, 2020).

### 6.6.2.2 Effects of non-government adaptation (B5)

The most common adaptation for commercial building is air conditioning, which is already being fitted in many new offices (Modern Building Services, 2017). In such a case, the impact of reduced labour productivity is removed, but at a cost (increased carbon emissions if air conditioning is not ultimately run off renewable sources, plus the expulsion of waste heat outside which can exacerbate the urban heat island effect). For instance, one large UK employer has set the objective of installing natural ventilation systems into all its offices instead of using air conditioning. This company has also introduced systems to encourage flexible working by promoting smart travel plans, enhancing video

and tele-conferencing facilities, providing employees with individual travel-reduction targets and reducing pressure on employees to attend face-to-face meetings. The company is inadvertently creating a work structure that is more adaptable to climate events – even though the main objective of their introduction was to reduce carbon emissions from work travel (a ‘no-regrets’ adaptation measure) (Trade Union Congress, 2009). Another example is Cleone Foods (Sustainability West Midlands, 2014), which has a local employment policy, with the majority of staff living in close proximity to the site. Remote working is encouraged by management, however new ways of working depend on access to resilient ICT and electricity infrastructure (for example, the company maintains dual main servers and mirrored hard drives).

It is unclear at the time of writing if the shift to higher levels of remote (home) working due to COVID-19 will be a long-term trend, but the current changes in working pattern effectively transfers management of a proportion of overheating risks from non-domestic buildings to private individuals. The latter may have much less adaptive capacity to undertake substantial modifications to their premises to manage overheating risks. However, it does increase the potential for softer measures such as appropriate clothing.

For infrastructure disruption, in our view it is unlikely that this will be remedied by non-governmental adaptation, and strong public action will be needed to ensure the productivity-related disruption due to infrastructure is minimised.

#### **6.6.2.3 Adaptation shortfall (B5)**

It is difficult to judge whether there is an adaptation shortfall on the basis of the evidence available because it is difficult to say how much autonomous adaptation will occur in the response to the risk. As such, the degree of current adaptation is likely to partially, but not fully address the risk.

#### **6.6.2.4 What are the barriers preventing adaptation? (B5)**

Overall the evidence of adaptation action being taken on the basis of existing guidance and regulations remains fairly anecdotal. There are a number of barriers to adaptation for this risk. The first relates to knowledge and risk information- there is a lack of widespread, robust estimates of the impacts of heat disruption on UK productivity – such information acts as a barrier. There is also a lack of meaningful evidence on the effectiveness of heat related interventions in improving productivity. The recent survey commissioned by the Welsh Government shows that Welsh businesses do not have the adequate information needed to mitigate risks, including information about how to assess risk (although there are plans to improve this). In addition, the financial costs of adaptation and the lack of internal capacity are cited as barriers to adapt. Support is needed in all three areas of risk management: understanding risks, measures, and how to act (Marshall & Allies, 2020).

Adaptation at the employee level depends on level of awareness and individual uptake and marginal gains from adaptation uptake remain unknown or vary by employee. As Xiang et al., (2013), highlight, reduced employee productivity has both physiological and psychological effects on high-

risk manual workers. More investigation is required into how employees can behaviourally adapt to increased workplace heat exposure (Xiang et al., 2013). Overall it appears that employees are willing to adjust working habits as a response to increased temperatures and receive more occupational health and safety training to do this (Xiang et al., 2016).

Business ability to address the shortfall depends on factors such as decision-making and employee consultation structure within an organisation and supply chain resilience to minimise infrastructure disruption (Trade Union Congress, 2009; IEMA, 2013). However, many of the physical measures are expensive, whilst others require additional time to prepare and implement. We believe that for small businesses such costs could be unaffordable, suggesting that governmental intervention (such as subsidy or regulation) will be needed to create enabling conditions. There are also potential areas for government to act, e.g. with efficiency standards for mechanical cooling.

Furthermore, there are also governance barriers, in that there is not a meaningful way for government, infrastructure operators and businesses or landlords to collaborate to better understand the issue and take further action.

#### 6.6.2.5 Adaptation scores (B5)

<b>Table 6.20</b> Adaptation scores for risks to business from reduced employee productivity due to infrastructure disruption and higher temperatures in working environments			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)	Partially (Medium confidence)

### 6.6.3 Benefits of further adaptation action in the next five years (B5)

#### 6.6.3.1 Additional planned adaptation that would address the adaptation shortfall? (B5)

The CCRA2 Evidence Report (Surminski et al., 2016) outlined a need to further research and understanding of the key interdependencies between business and infrastructure, the types of employment at greatest risk and the effectiveness of planned or autonomous adaptation. Collecting business continuity information on productivity and extreme weather is critical to understanding this risk better.

Adaptation reporting could help to increase uptake and encourage businesses to prioritise this risk, but a requirement would be needed to include productivity risks in reports, which is challenging given the current voluntary approach to reporting adopted by the UK Government.

Very few studies have looked at either the risk or adaptation underway in the UK, suggesting further investigation is required across the UK to better quantify both the scale of the problem, and the

benefits of implementing measures to address it both in current and future climates. In particular, evidence for future risk from reduced employee productivity is limited.

#### 6.6.3.2 Indicative costs and benefits of further adaptation action (B5)

There is some information on various adaptation options to reduce heat in commercial buildings and also linkages to the information available for domestic buildings (see the discussion of low and no-regret options for risk H1, Chapter 5: Kovats and Brisley, 2021). Day et al. (2019) assessed 17 adaptation measures (drawn from a longer list of over 30), including both solutions for indoor and outdoor work, to address higher base temperatures as well short-term temperature peaks. The authors estimated the 'potential scale of impact' as well as the 'feasibility' of the measures. This also includes analysis of which actions can be taken forward by the private sector, by government and by individuals. The study also considers the economic costs of each adaptation measure including direct financial costs of implementing the measure, and a range of 'indirect' costs. Costa et al. (2016) also estimated averted losses from alternative adaptation measures for three case study cities (Antwerp, Bilbao, and London) for a warm year at the end of the century (2081-2100). These studies identify a range of low and no-regret adaptation actions.

Some opportunities for labour productivity adaptation are identified such as transition to new ways of working (remote working, flexible working) and low carbon and energy efficiency buildings to maintain employee productivity (ILO, 2019, Day et al., 2019). These behavioural changes have been tested and employed by various businesses with the onset of the COVID-19 pandemic, but longer-term behavioural change is yet to be seen. Moreover, there are occupational and sectoral divergences in the uptake of new ways of working, with some professions lending themselves better to flexible working than others.

Increasing collaboration and strengthening governance in this space may also deliver benefits in the next five years. Better collaboration between business, building owners, government and infrastructure operators could help facilitate adaptation. These efforts could replicate the engagement and collaborations seen in the flooding space and be linked to net-zero initiatives, recognizing that heat poses challenges for reaching net-zero.

With regards to nature-based solutions as a potential adaptation response to extreme heat, there is emerging literature estimating the climate benefits of urban natural capital at the UK scale (Eftec et al., 2018). This valuation methodology provides estimates of temperature reduction in city areas and benefits, which feed into the Natural Capital Accounts by ONS (ONS 2018). Although experimental in nature, these estimates give a sense of the scale of benefits (particularly in terms of avoided loss of productivity) and how these might rise over time with an increasing frequency of 'hot' days. For instance, in 2017, the annual benefits of cooling from green and blue space in urban areas was estimated at £244m, with London dominating the benefits (reflecting the climate of London, the scale of its economy and the unusually large area of green space for such a big city). The ONS 2018 assessment uses analysis from Eftec (Defra, 2018a) and is based on Costa et al.'s (2016). However, increasing the area of large natural spaces in urban areas, in response to rising climate risks, appears challenging, not least because of the opportunity cost of land. Initiatives led by the private sector such as 'Living roofs and walls – from policy to practice' aim to address these issues.

### 6.6.3.3 Overall Urgency scores (B5)

<b>Table 6.21</b> Urgency scores for risks to business from reduced employee productivity due to infrastructure disruption and higher temperatures in working environments.				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency Score</b>	Further investigation	Further investigation	Further investigation	Further investigation
<b>Confidence</b>	Low	Low	Low	Low

Despite growing understanding of heatwaves and infrastructure disruptions there is still little assessment of labour productivity implications across different sectors and context, including indoor and outdoor processes, although Wales has recently gathered additional survey evidence. Across the UK the risk is currently deemed low but could increase to medium and high if not managed. There are benefits to further investigation over the next five years, in particular considering the interplay between changes to infrastructure resilience, employee health, and net zero ambitions. This urgency score is predominantly based on expert judgement.

### 6.6.4 Looking ahead (B5)

A key focus here is on improving the evidence base through further investigations. Reporting will play a role. Adaptation action will also depend on level of collaboration between businesses, infrastructure providers and government. CCRA4 should consider the interplay between air conditioning and other cooling devices and investigate how hotter summers could put a strain on the feasibility of reaching Net Zero carbon targets.

## 6.7 Risks to business from disruption to supply chains and distribution networks (B6)

Extreme events are already a significant cause of supply chain disruption across all sectors with exposure to climate hazards set to increase in the future. Some action has been taken by business and there are opportunities from advances in technologies and from the learning and increased focus on supply chain resilience following the COVID-19 crisis. However, it is unclear if this will keep pace with the increasing risk or how effective it will be. Therefore, more action is needed but with a low certainty in the evidence, which is skewed towards larger companies, the food sector and self-reporting. This is applicable across England and all DAs, but more work is needed to understand regional differences. The evidence base is strongest for England, followed by Scotland, with less for Northern Ireland and Wales. International supply chain aspects are covered in Chapter 7 (Challinor and Benton, 2021).

### 6.7.1 Current and future level of risk (B6)

Note: it has not been possible to split the evidence by UK country for this risk.

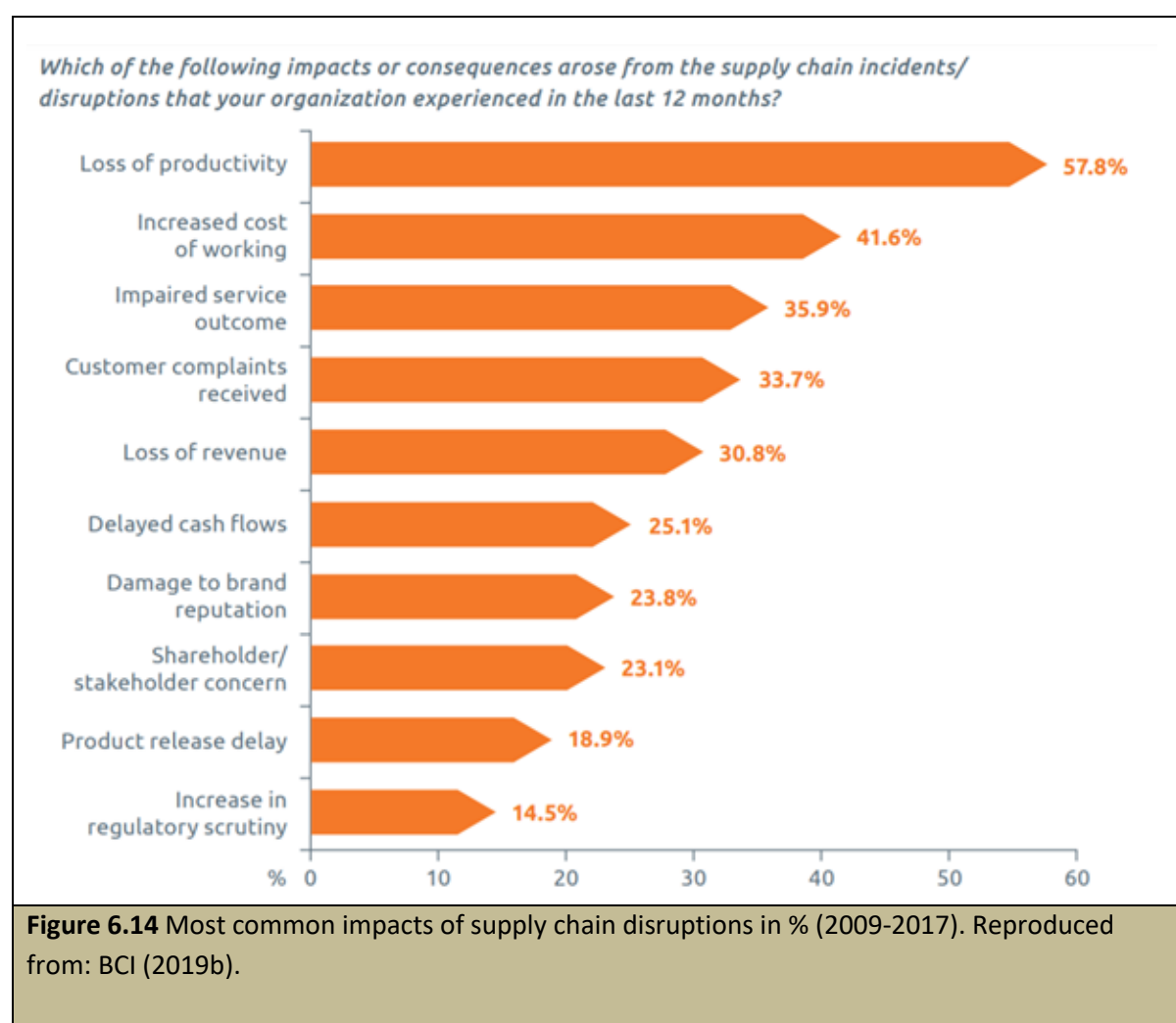
#### 6.7.1.1 Current risk (B6)

The risk level varies according to location and sector. Factors such as reliance on single transport routes or how specialised the supply chain is can have an influence. McKinsey (2020) suggested that highly specialised supply chains e.g. for semi-conductors, lead to more severe impacts for downstream players as supply of a critical input may only be available from the source that has been disrupted. However, the more commoditized the supply chain is, the larger the number of downstream players that may be affected by spiking prices from a sudden reduction in supply. Looking specifically at disruption to the agriculture products supply chain, the UK food supply system has shown to be overall resilient. However, this cannot be taken for granted as the experience with COVID-19 and the disruption due to sudden border closures over Christmas food (affecting ports such as Dover) show. Overall CCRA2 established lack of evidence on how business disruption translates to UK risks, as also highlighted by Manning and Soon (2016). More recently a survey by the Business Continuity Institute found extreme weather to be the second most highly rated cause of disruption in 2018 (after IT outages) and has been consistently highly rated over a number of years (BCI, 2019a; BCI, 2018a). Weather hazards also contribute to other causes of supply chain disruption reported separately, such as travel network disruption, outsourcer failure, Health and Safety (H&S) incident and fire.

These disruptions have various negative impacts, as outlined below looking at a disruption distribution between 2009-2017, as highlighted by a BCI survey (Figure 6.14).

The LSE Climate Risk Business Survey (2020) finds that only 9.9% of the respondents who experienced losses due to supply chain and distribution network disruption were able to quantify the impacts. And while here there is little evidence to relate the source of disruption to the consequences, adverse weather events tend to particularly aggravate logistics costs (BCI, 2018a). For example, a preliminary analysis by UNCTAD (2020) shows that a 2% reduction in China's exports to foreign car manufacturers could lead to a \$7 billion reduction in global automotive exports. When companies have to cease trading the average period of shutdown is 3 months. 1 in 5 small businesses say they would not survive more than a month of shutdown (Crisis Control, 2017).

HSBC (2020) differentiate between acute one-time climate disruptions and chronic, longer-term disruptions which can increase supply cost, lower quality, delay delivery or lead to the need to use alternative supplies. They also note that climate change is different than other shocks for supply chains due to more frequent, severe and longer-duration supply chain disruptions, disruptions in more places, disruptions during transitions and focusing more investor attention on a company's supply chain related greenhouse gas (GHG) emissions (HSBC 2020).



Some organisations and sectors are more exposed to climate hazards through their supply chains than others. Industries that are part of the food system, for example, rely on agriculture, which is particularly exposed to weather and climate, and long distribution networks, with 50% of food consumed in the UK imported from 180 different countries (Watkiss, 2019; Defra, 2017; Defra, 2018a). Even within the UK, agricultural and food supply chains experience disruptive impacts with milk and beef processors suffering most impact from reduced raw materials (Farmers Weekly, 2020).

The Climate Resilience in the UK Wine Sector project (CREWS-UK, 2021) looks at how climate variability interacts with the broader viticulture value chain that connects producers to final markets. It describes how the impacts of climate shocks can be transferred through the activities, resource flows and actors along value chains (Carabine et al., 2018; Canevari-Luzardo, 2019; Codjoe & Owusu, 2011) while business networks and interdependencies also dampen impacts to other actors along the chain (Canevari-Luzardo, 2019) and support access to resources, (e.g. inputs and downstream activities such as storage, processing and marketing activities) and adaptation of other actors within value chains (Carabine et al., 2019; Gannon et al., 2021a). Stakeholder discussions as part of the CREWS project highlight several supply-chain issues (CREWS-UK, 2021):

- *‘E.g. with restaurants and retailers – hard to build reliable longstanding relationships when can’t reliably meet demands. Variability puts challenges on that. Especially it’s very difficult to turn*

*taps on and off with these things. If you can't, if you are supplying someone and then next year you can't, it's very difficult to build that trust relationship back up again. To increase volume. So, maintaining long-term relationships can be more challenging with variability.*

- *Business relationships structured vulnerabilities and adaptive capacities – e.g. contracts. These business relationships – and thus adaptive capacity – are not stable, with climate and variability in yields shaping them too.*

Section 7.3 of Chapter 7 (Challinor and Benton, 2021) considers risks to UK food availability from climate change overseas, including the potential for cascading and interacting risks associated with supply-side disruptions.

It is not just individual companies that are exposed to supply chain risks. Extreme events have the potential to affect the profitability of entire sectors through impacts on local and global supply chains. For example, in the US, Hurricane Harvey in 2017 caused disruption to oil transport and distribution networks and led to a 20% increase in fuel prices across the country (Marsh & McLennan Companies, 2018; Department for International Trade, UK Trade in Numbers, February 2020). In 2016/17 the UK saw shortages and high prices of an array of vegetable crops due to a combination of weather factors (storms, cold, snowfall, heavy rainfall, flooding) affecting growers in Spain, Italy and across Europe. In particular, courgette prices rose by 60%, aubergines by 132% and tomatoes by 45% and UK retailers resorted to air freighting lettuces and other items from the US to plug the gap (Crisis Control, 2017). However, so far the UK food system has been resilient to supply chain disruption due to diversity, flexibility and the competitive nature of the industry (Colwill et al., 2016; Defra, 2017b; Defra, 2018; Watkiss, 2019). This has been demonstrated during disruptive challenges in recent years e.g. 2015 flooding, 2009 H1N1, 2010 volcanic ash and 2014 industrial action (Cabinet Office, 2019). However, very short lead times and non-warehousing of stock is likely to cause challenges in times of disruption, as seen with COVID-19-related disruptions in 2020.

There is a lack of UK based evidence to support any analysis of the risk to entire sectors from supply chain disruption beyond the food system. But it is worth noting that other sectors are at least as important, if not more so, to the UK economy. According to McKinsey (2019) the top five commodity groups in terms of share of total UK trade in 2018 were transport equipment (17%), chemicals (15%), non-electrical machinery (14%), minerals and metals (14%) and agricultural products (9%).

At the time of writing there has not yet been a full analysis of the supply chain effects of COVID-19 pandemic in the UK. There is anecdotal evidence of market effects and demand side disruption, caused by behaviour change (e.g. stockpiling) and the economic impacts of the lockdown, but this requires further investigation to understand the significance of these factors with respect to climate related disruptions.

#### 6.7.1.2 Future risk (B6)

Climate change is likely to contribute to an increase in exposure to supply chain disruption by driving an increasing frequency of adverse weather events and evolving climate hazards both in the UK and overseas. Unsurprisingly, businesses are self-reporting that weather and climate hazards are a driver



of future supply chain risks (CDP, 2018; LSE, 2020). Respondents to the LSE Climate Risk Business Survey (2020) reported that while heavy rainfall and surface water flooding and high temperatures, including heatwaves, will continue to dominate, coastal and river flooding and water scarcity will also become more significant drivers. In the CDP survey (2018), those supply chain risks with a substantive financial or strategic impact were mostly scored as medium term, of medium magnitude and (with less agreement) likely. This evidence, although self-reported and uncertain, suggests future risks to be greater than current.

The reliance of UK businesses on overseas markets creates exposure to climate change impacts abroad. For example, the combination of changing rainfall patterns and increased temperature could lead to a reduction in crop production in arid and semi-arid lands (ASAL) of 20-50% by 2070 (Sarr, 2012; Alberto et al., 2015). Similarly, risks from pests and diseases, long term soil erosion, port closures, power outages, oceans acidification effects on cod (WWF, 2018), extreme heat effects on workers (Alberto et al., 2015) and financial pressures on the supply chain, particularly farmers, in the wake of severe events (WWF-UK, 2018) could all increasingly find their way to UK businesses via supply chains. The manufacture and supply of food, clothes and electronic equipment are understood to be particularly exposed to international climate change impacts (CCRA2). Industries with single key supplier locations in areas subjected to significant climate change impacts are more exposed e.g. significant sea level rise will adversely impact manufacturing and shipping routes located around the main Chinese river systems (Xu, 2016). This underpins the UK's vulnerability to global supply chain, which is covered in greater detail in Chapter 7, Section 7.2 (Challinor and Benton, 2021).

As risks to individual businesses increase and effects become more frequent and widespread, there are social and economic risks due to the effects on exchange rates, of commercial failure, higher prices, shortages or fluctuations in quality of food or other vital materials. For example, UNEP-FI and Acclimatise projected yield decreases in US coarse grains, oil seeds, wheat and rice of up to 25% by 2050s for a scenario of approximately 4°C global warming by the end of the century<sup>14</sup>, and that correspondingly commodity prices are expected to rise by up to 20% (UNEP-FI and Acclimatise, 2018). Meanwhile, recent research carried out on the impacts of climate change on the dairy industry on the island of Ireland, revealed emerging concerns among farmers and agri-food businesses about extreme weather events globally, and the indirect, economic impacts on feed grain prices (Safefood, 2017). Another study looked at the potential impacts of climate change on the interplay of supply chain shocks and a sector's export value (COACCH, 2019), based on input-output connectivity between sectors and countries, along with data on extreme weather. The findings suggest that, if no additional adaptation were to occur, climate change will reduce a sector's export value by up to 16 percent. However, these findings vary strongly between countries as well as sectors with the strongest impacts in the tropics due to the stronger projected climate impacts, which are then transmitted over interregional supply chain connections.

Future risk will also depend on the attributes of future supply chains (e.g. length, complexity, interconnectedness and nature of relationships). The current trend for increasing complexity and interconnectedness brings growing uncertainties and challenges relating to managing risk through

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<sup>14</sup> Multi-model mean of the CMIP5 ensemble with the RCP8.5 concentration pathway.

others (Crisis Control, 2017) but could also provide flexibility that helps systems absorb shocks (Colwill et al., 2016). Companies may take action in response to EU exit or the COVID-19 pandemic or other priorities, changing strategies and setting new trends that affect the future climate risk (discussed further below).

The potential impact of EU exit on UK supply chains has created the need for additional understanding on climate risks and opportunities. The UK currently imports mainly from Germany (11.6% of total value of imported goods and services), followed by the US (11.4%) and the Netherlands (7.3%) (DIT, 2020), but this distribution is likely to change depending on new trading relationships. For food supply chains in particular, the UK currently performs highly on sustainable agriculture indexes at the EU level (Agovino, 2019) but as trading partners change, there is a need to reassess extreme temperatures and water scarcity in source countries (Benton et al., 2019). One example is the UK's increased dependence on imports of fruit and vegetables; UK domestic production of fruit and vegetables decreased from 42% in 1987 to 22% in 2013. Importing more from climate-vulnerable countries could reduce the availability, price and consumption of these products in the UK.

#### 6.7.1.3 Lock-in and thresholds (B6)

##### 6.7.1.3.1 Are there lock-in risks?

Supply chain risks can be locked in if UK companies invest in transport routes, distribution hubs or production centres that are more exposed or vulnerable to climate hazards. It is not clear from the evidence if these factors are taken into account in investment decisions of this nature. However, there is some evidence that other priorities may be leading to trends that increase lock in. Such as centralised production for reasons of efficiency or over reliance on technology and software. While these offer huge opportunities for understanding and managing supply chain risks, they could bring new problems as has been seen in finance and banking sectors (Colwill et al., 2016). This also underlines the importance of infrastructure to ensure that technology can be used.

##### 6.7.1.3.2 Are there potential thresholds?

Thresholds that exist for producers and transport operators will also have significance throughout their supply chains. A global survey of ports found that less than 40% are able to report the availability of thresholds for climatic stressors that could impair the integrity and functionality of infrastructure and equipment (Asariotis et al., 2017). This indicates either information or internal communication gaps. There may also be thresholds for switching suppliers based on prices including the cost of air freight from alternative sources or of alternative products. For example, disruption to soymeal supply, gives rise to use of alternative chicken feeds such as insects and algae (WWF-UK, 2018). An example of thresholds potentially being breached are the increased customs requirements as a result of new trade deals which might see a shift in trading patterns or a re-orientation of some businesses.

#### 6.7.1.4 Cross-cutting risks and inter-dependencies (B6)

Supply chains create a network of interdependencies, through which UK businesses can be exposed to all of the risks faced by their suppliers, producers, transport routes and customers with significant potential for interaction between (Alberto et al., 2015). In particular, transport network disruption, which is often triggered by adverse weather (BCI, 2019a), was reported as a source of significant disruption in the BCI survey by 27% of companies (BCI, 2018b). Ports are vital to UK supply networks and can be affected by weather and climate change in a variety of ways, including effects on the operation of port infrastructure which is explored further in Chapter 4 (Jaroszewski, Wood and Chapman, 2021). A survey of global ports found that the majority suffered some or significant impacts due to weather/climate related events including 60% reporting delays. However, European ports seem to be less affected (Asariotis et al., 2017). Since ports are not subject to economic regulation, there is a general lack of data on the resilience of ports compared to regulated sectors, as outlined in Chapter 4 (Jaroszewski, Wood and Chapman, 2021).

Socio-political factors specific to suppliers' countries can interact with the climate, such as conflict, migration, global financial pressures and political protectionism (Marsh & McLennan Companies, 2018). In particular, firms in arid and semi-arid lands face significant constraints from degraded natural resources and infrastructure; conflict over resource allocation and; increasing population (pressure on resources, food security) (Alberto et al., 2015). Alternatively, the effects of climate change can simply coincide with other factors exacerbating the consequences of both. For example, in 2008 drought, rising oil prices and competition for land were all factors in a food crisis which saw wheat prices increase by 130%, soy by 87% and rice by 74% (WWF, 2018). Similarly, the price of avocados increased by 50% in the first half of 2017 when a late harvest and floods coincided with a worker strike in Peru. There may also be issues for domestic food production. For example, The Welsh's Government's Capability, Sustainability and Climate Report (CSCP05), looks at the effects on crops and shows a clear risk with greater volume and intensity of rain in the winter / spring periods and changing timing of access to land. However, there are also potential greater cultivation opportunities (Welsh Government, 2020).

Disruption to supply chains and distribution networks due to physical risks can also link to transition risks or legal risks (see implications of Net Zero below). Moreover, as the NFU highlights (NFU, 2020), businesses may fail to meet supply contracts as a result of supply chain disruption (e.g. crop failure during extreme dry weather). This poses additional legal risks to businesses which are beyond the scope of CCRA3.

The LSE Climate Risk Business Survey (2020) suggests UK businesses are exposed to weather related supply chain risks through dependencies on suppliers and transport networks in equal measure. The latter may be more significant in Scotland, Wales and Northern Ireland due to dependence on a more limited number of transport hubs. However, The Welsh Government survey of businesses referenced in section 6.7 did not show evidence of perceived infrastructure disruption as a risk to their supply chains.

In Section 7.2 of Chapter 7 (Challinor and Benton, 2021) we present a framework of the most common transmission pathways in which risk may cascade into the UK: through energy, finance and markets, governance, IT and information, movement of goods, movement of people and wellbeing.

#### 6.7.1.5 Implications of Net Zero (B6)

The UK Net Zero target only applies to domestic emissions, and not emissions associated with international production and transport to the UK. It does, however, apply to emissions associated with production and transport within the UK, and these supply chains will need to move to Net Zero over time. It is not clear how this difference will affect the structure of supply chains, but if it does, it will have implications for climate risk profiles. For instance, reduced stock holdings and centralised production may be more resource efficient but less resilient (Colwill et al., 2016).

The trend for shorter supply chains and localised production, driven by resilience considerations or in response to climate hazards, could affect Net Zero ambitions. While this could reduce transport-driven emissions, in many cases, much higher emissions are associated with local production, and thus the net effects (local versus international supply) depend on the comparative emissions from production (for an example, see the food miles debate, Webb et al., 2013). Nonetheless, emissions reductions may be in conflict with resilience objectives.

There is anecdotal evidence that during disruptive events, business responses can be energy and emissions intensive (e.g. sourcing from further away including air freighting) (PES Media, 2020). Thus it is possible that, with rising climate extremes, supply chain risks could make Net Zero slightly harder to achieve.

The drive for Net Zero could also result in supply chain pressures for materials such as rare earth metals due to rapid growth in clean technologies, leaving them more vulnerable to climate related disruption (McKinsey, 2020).

#### 6.7.1.6 Magnitude scores (B6)

While organisation-level information exists, there is little UK-wide information on the current size of extreme weather disruption to supply chains of business sectors outside of the food sector, and no national estimate for any sector of the total average annual economic damage exists. Expert judgement leads to a medium magnitude with £tens of millions economic damage or foregone opportunities for England and £millions for the rest of the country. However, there is only low confidence due to a limited evidence base. For future risk, numerous studies point to supply chain shocks as a potentially large driver of risk, particularly for food supplies, but the evidence available does not provide a measure of estimated annual damage in £ and so cannot be estimated using the CCRA methodology at present.

**Table 6.22** Magnitude scores for risks to business from disruption to supply chains and distribution networks.

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Medium	Unknown	Unknown	Unknown	Unknown
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Medium	Unknown	Unknown	Unknown	Unknown
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Medium	Unknown	Unknown	Unknown	Unknown
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Medium	Unknown	Unknown	Unknown	Unknown
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

## 6.7.2 Extent to which the current adaptation will manage the risk or opportunity (B6)

### 6.7.2.1 Effects of current adaptation policy and commitments on current and future risks (B6)

#### 6.7.2.1.1 UK-wide

Since CCRA2 some progress has been made in driving adaptation in supply chains through government organisations' own procurement processes. Furthermore the UK Government has announced a consultation to improve the way in which it takes account of social value in awarding contracts to suppliers, including adapting to climate change.

However, the UK Industrial Strategy does not make any references to helping supply chains become more resilient to the impacts of climate change. According to the LSE Business Survey businesses are unlikely to turn to government for information and support when seeking to manage climate risks to their supply chain, instead preferring to make use of their own in-house expertise or consultant services.

#### 6.7.2.1.2 England

The plans for supply chains in the second National Adaptation Programme (NAP2, Defra, 2018b) focus on food security and Defra has well established mechanisms for working with the food sector, helped by contingency planning for EU exit and working with the Food Chain Emergency Liaison Group to build on research into food supply resilience (UNEP-FI, 2019). However, NAP2 does not set out actions to address the risks that England faces from the international impacts of climate change on supply chains, or sectors other than food. There are also no stated goals for adapting supply chains to climate change or specific planning for scenarios of either 2°C or 4°C global warming by the end of the century. The Environment Agency have also amended their procurement process to take account of changing risks from weather and climate.

#### 6.7.2.1.3 Northern Ireland

In Northern Ireland, supply chain disruption caused by the recent COVID-19 pandemic affected the supply of core components for manufacturing companies and also the supply of key PPE items. This has highlighted the need for companies to put more emphasis on understanding and managing the risk in their supply chains to ensure that they can build in resilience. Invest Northern Ireland have developed a supply chain risk assessment checklist to support companies to review this and are actively working on further solutions to support supply chain resilience (Invest NI COVID-19 Response, 2020). These include dual sourcing, re-shoring or near shoring elements of their supply chain. Regarding the agriculture sector in Northern Ireland, the Going for Growth (GfG) report proposes an integrated supply chain from farm to customer but does not explicitly address critical elements of the supply chain that are upstream from regional farm production processes, such as, imports of feed, fuel/energy, fertilizer and other agri-chemicals (Safefood, 2017).

#### 6.7.2.1.4 Scotland

In Scotland, the supply chain disruption faced by businesses is addressed via the Scotland's Climate Ready Business Guide (Adaptation Scotland, 2019) and SCCAP2 (Scottish Government, 2019). Businesses are encouraged to consider alternative suppliers, diversify their network and focus on local markets.

#### 6.7.2.1.5 Wales

The Welsh Government's CSCP05 Report considers crop suitability and implications for food supply chains. This report uses soil, site and climate information to model the potential land suitability for 118 crops under nine projected UKCP18 climate change scenarios, as well as under present day conditions (Welsh Government, 2020). This builds on earlier work from ADAS Research (2014), who conducted a Review of Land Use and Climate Change, assessing the evidence base for climate change action in the agriculture, land use and wider food chain sectors. The research identifies risks to domestic and business property, livestock grazing; availability of feed, yield impacts in the arable/horticulture and forestry sectors; pest and disease pressure; species water stress and wind throw in forestry; wildfires, affecting both grassland and forestry areas (ADAS Research 2014).

#### 6.7.2.2 Effects of non-government adaptation (B6)

In terms of business actions an analysis by HSBC (2020) divide these into bridging and buffering: Bridging involves the buying organisation taking action to help build up the capacity of its suppliers to manage through and recover from disruptions. Buffering involves the buying organisation taking action to protect itself from the consequences of supplier failures. Bridging strategies include collaborative planning and control, financial support and strengthening relationships with suppliers. Buffering strategies include inventory, capacity, liability, lead time and cost buffer (HSBC 2020). Survey evidence from the Business Continuity Institute (BCI, 2019a; BCI,2018a) shows that many businesses are taking buffering action to manage risks from supply chain disruption. These are not specifically in response to climate risks. Plans includes some hard engineering solutions, such as improved storage facilities and the building of fusion centres, which enable resilience by bringing down silos (BCI, 2018a reported that 30% of organisations have fusion centres and 14% planning to build one in the next 2 years) and technology for monitoring, measuring and reporting on performance affecting supply chain disruption. However, softer measures such as engaging with staff and business continuity planning (BCI, 2019a) seem to be on an equal footing for supply chain risks (CDP, 2018 and LSE, 2020). The majority of businesses have business continuity arrangements in place to deal with supply chain disruption and are increasingly aligning with or being certified to the ISO 22301 international standard on supply chain management (BCI, 2019a). The Co-operative Group for example, has established business continuity programmes, mandatory supplier checks and monitoring, and conducts disaster recovery tests (The Co-operative Group, 2018). There has also been an increase in insurance coverage although supply chain losses are rarely fully covered (BCI, 2018b).

In terms of bridging actions, most companies talk to new and existing suppliers about their business continuity plans: the 2018 BCI supply chain survey found that 72% of respondents do this. Almost half of the survey respondents claimed that more than 60% of their suppliers have business continuity in place to deal with supply chain disruptions, while roughly a quarter report that to be the case for 80% or more of their suppliers (BCI, 2018b). The number of organisations requesting alignment to a known standard has increased from 36.5-51% since the launch of ISO22301 in 2012 and checks for certification increased from 11-51% (BCI, 2019b). However, a global survey of ports found that, despite extensive past experience of impacts, most ports had not received any related requests for effective response measures from their users/clients (Asariotis, R. et al., 2017).

More collaborative approaches along supply chains are also on the rise. According to BCI's survey (BCI, 2019a) there has been an increase from 13.3% (2018) to 25.6% (2019) of respondents carrying out joint exercises with their suppliers. This trend appears particularly evident in the highly competitive food retail sector, with companies engaging with their suppliers, driven by the desire to expand globally to source cheaper raw materials (Colwill et al., 2016).

#### 6.7.2.3 Is there an adaptation shortfall? (B6)

It is unclear how the plans and actions described above will actually reduce the risk to supply chain disruption from climate change. Business continuity arrangements mean supply chain risks are more likely to be insured (BCI, 2018) and less likely to lead to (Crisis Control, 2017). However, most

businesses don't analyse the original source of disruption when recording, measuring and reporting supply chain disruption (BCI, 2019a; BCI, 2018b) so it is not clear how these arrangements are reducing climate driven supply chain risks specifically. Moreover, they do not seem to affect the level of loss when one does occur (BCI, 2018b).

Nevertheless, over the past decade, supply chain partners (along with customers and investors) have started raising issues regarding climate change with increasing urgency and frequency (Marsh & McLennan Companies, 2018).

The evidence, although weak, implies an adaptation shortfall. Some of the shortfall can be expected to be addressed by business action, in particular in building business continuity capability and driving resilience through supply chains. This is demonstrated by increasing use and uptake of the ISO standard on supply chain management. EU exit preparations and the COVID-19 response may accelerate this as experience during 2020 suggests that companies that prioritised efficiency over resilience are ill-prepared for disruptions (YGCP, 2020).

However, it is not clear from the evidence how these actions will translate to reduced risks from climate-related disruption as the source of disruption is not routinely analysed.

#### 6.7.2.4 What are the barriers preventing adaptation? (B6)

There appear several cultural, institutional and commercial barriers to adaptation including:

- **Integration in business processes:** Only 36% of businesses integrate business continuity in their procurement process, while 20% don't mention it in supplier discussions according to BCI, 2018a.
- **Traceability:** According to the WEF survey fewer than 15% of executives feel that their current capabilities are sufficient to track physical risks consistently (WEF, 2020). This was also confirmed in stakeholder discussions, with a leading climate adaptation advisory firm stating that many of their clients cannot provide the necessary level of traceability in product components/ ingredients that allow for an assessment of physical climate risks in their supply chain to be undertaken with sufficient granularity (Stakeholder discussions).
- **Data barriers:** This includes unreliable data from supply chain partners and a lack of standardisation for data exchange and the calculation of metrics. There are also technological barriers, such as the absence of end-to-end platforms, and organisational barriers, such as untrustworthy data-sharing mechanisms or privacy concerns. (WEF, 2020), making it difficult to validate supplier's business continuity arrangements (BCI, 2018a).
- **Knowledge and understanding of risks:** Scenario analysis is constrained by gaps in knowledge or understanding for example due to modelling uncertainty (Marsh & McLennan Companies, 2018) and a risk perception that may be out of step with reality. Adverse weather is only ranked 4th in terms of concern over next 12 months and 3rd over next 5 years despite being the second most prevalent cause of supply chain disruption (BCI, 2019b).
- **Institutional constraints,** particularly for international contexts: For example, crop insurance is not readily available in many developing countries and comes with limitations such as lack of data or unaffordability for farmers (Marsh & McLennan Companies, 2018).



- **Competing objectives:** There are tension between goals on resilience, sustainability and efficiency. For example, the dominance of lean manufacturing principles driven exclusively by cost control tends to result in concentrations in areas of cheap labour and shrinking numbers of key suppliers (BCI, 2018b). This increases both the likelihood (due to length of supply chains) and consequence (due to high dependencies on single suppliers or places) of weather-related disruption. It also increases vulnerability to the weather. See also section 6.7.1.5 on Implications of Net Zero.
- **Commercial barriers:** Demand for low prices and evolving customer requirements (retail and food industries in particular) could be constraining resilience (Marsh & McLennan Companies, 2018; Colwill et al., 2016).

Overall, the confidence in evidence about adaptation action remains low – it is mostly from surveys and based on assumptions about the relationship between business continuity and climate change.

#### 6.7.2.5 Adaptation scores (B6)

<b>Table 6.23</b> Adaptation scores for risks to business from disruption to supply chains and distribution networks.			
<b>Are the risks going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

#### 6.7.3 Benefits of further adaptation action in the next five years (B6)

##### 6.7.3.1 Additional planned adaptation that would address the adaptation shortfall? (B6)

The majority of further actions involve capacity building, institutional changes, or the development of new strategies, technologies or ways of working, which will take time to develop, test and implement. Therefore, there is a benefit to putting these in place within the next five years even where the climate-related risks are not immediate. Indeed, the BCI recommends an offensive rather than a defensive approach (Marsh & McLennan Companies 2018), while McKinsey (2020) finds significant potential for many industries to adapt in the next decade. For example, in the case of rare earth metals they estimated that 50-80% of risk could be eliminated if adaptation measures were implemented (McKinsey 2020). Furthermore, many of the actions can be seen as ‘no-regrets’ options business continuity planning that builds resilience in supply chains or improves the quality of business relationships offers immediate benefits.

Strategies that businesses could take to further build resilience include:

- Product diversification or geographical diversifying (WWF, 2018).

- Scenario analysis to ensure plans are robust under different plausible outcomes by explicitly defining and separating external scenarios from internal plans (Marsh & McLennan Companies, 2018).
- Ensuring risks are incorporated into risk registers and management programmes so that optimal resources and opportunities to improve corporate performance and earnings can be identified (BCI, 2018a).
- Intensification in the use of storage facilities (COACCH, 2019).
- More 'bridging' actions, that is, inclusion of supply chain partners in risk assessments, planning and communications (Crisis Control, 2017). Given the post-EU exit uncertainty due to changing supply chains Tim et al. (2019) recommend more investment in the agricultural systems of source countries in order to minimise climate risk. And the World Business Council for Sustainable Development (Landworkers' Alliance, 2019) recommends adopting a circular model for resilience, with shocks and stressors in the food, agriculture and forestry sector, being met with adaptation response and transformation of existing business models and supply chains.
- Making more use of technology to improve traceability mechanisms (YGCP, 2020) and to predict, monitor, record, measure or report supply chain risks and communicate with suppliers. For example, using automated communication and notification systems, BCM platforms, incident management platforms or social media monitoring (favoured by SMEs) (BCI, 2018b; BCI, 2019a).
- Expanding firm level insurance coverage of physical risks to supply chains, including by use of new products such as non-damage supply chain insurance plans and parametric insurance (for example, with pay-outs based on a drought duration index or rainfall data rather than losses) or captive insurance solutions. The latter can improve climate resilience by strategically funding risk exposures, preparing for a worst-case scenario in the face of increasing frequencies and by accessing reinsurance markets and alternative capital markets to fund less predictable risks (Marsh & McLennan Companies, 2018; BCI, 2019a).

There are roles for both the public and private sector in driving resilience through supporting or/ incentivising their own supply chains to implement adaptation measures by:

- Requiring physical risk disclosures and setting contractual arrangements that take adaptation into account (UNEP-FI and Acclimatise, 2018).
- Using resilience criteria with choosing suppliers as part of procurement processes (Crisis Control, 2017). For public sector procurement, the Public Services (Social Value) Act provides a potential tool by requiring commissioners of public services to think about how they can also secure wider social, economic and environmental benefits. (Source: CCRA3 Stakeholder Event, February 2020)
- Helping suppliers reduce their own risks (Crisis Control, 2017). For example, the water stewardship approach provides companies with a means of committing resource and using influence to support good water practices in areas of weak governance.
- Promoting business continuity, with a particular focus on strategies that achieve multiple goals including resilience and sustainability for which there may be market failures. For example, distributed manufacturing, seasonal produce and local sourcing have a role to play in achieving both sustainability and resilience goals (Colwill et al., 2016).

There is also a role for government in capacity building and setting the right institutional environment (COACCH, 2019), such as by:

- Promoting the establishment of binding supply chain due diligence legislation on a national level while ensuring international alignment (YGCP, 2020).
- Promoting the coherent use and development of modern traceability technology, namely blockchain (YGCP, 2020).
- Supporting improved climate and location-based information and integration with other types of information (UNEP-FI and Acclimatise, 2018).

Taking into account all three steps of the urgency assessment we conclude that more action is needed, but with a low certainty in the evidence, which is skewed towards larger companies, the food sector and self-reporting. The reliance on overseas markets means UK supply chains are exposed to climate impacts abroad with exposure increasing due to climate change. While some action has been taken by businesses and others on supply chain resilience and there are opportunities from advances in technologies, there are many barriers to adaptation. It is unclear how effective current and planned actions will be in managing climate or weather-related disruption specifically. The COVID-19 crisis may lead to companies and entire industries rethinking their global supply chain model. This presents an opportunity for step change in government action to facilitate this and achieve multiple benefits.

This is applicable across all DAs, but more work is needed to understand regional differences. The evidence base is strongest for England, followed by Scotland, with less for NI and Wales.

#### 6.7.3.2 Indicative costs and benefits of additional adaptation (B6)

There are some aspects of climate change risks and responses that have been quantified for food supply chain resilience. Even here, however, there is little information on the associated costs and benefits (in aggregate), as identified by recent review of food supply chains and adaptation (Watkiss et al., 2019), though it did identify potential adaptation measures and their potential (qualitative) benefits and costs, indicating net beneficial further actions exist.

#### 6.7.3.3 Overall urgency scores (B6)

The urgency score is driven by the medium current magnitude and the potential for major disruption to supply chains from extreme weather in future, although future magnitude is unknown. There is limited evidence for effective analysis and adaptation measures. There are benefits to more action to help quantify and manage risks. The majority of these beneficial actions involve capacity building, institutional changes, or the development of new strategies, technologies or ways of working, which will take time to develop, test and implement.

**Table 6.24** Urgency scores for risks to business from disruption to supply chains and distribution networks.

Country	England	Northern Ireland	Scotland	Wales
<b>Urgency Score</b>	More action needed	More action needed	More action needed	More action needed
<b>Confidence</b>	Low	Low	Low	Low

#### 6.7.4 Looking ahead (B6)

For the next CCRA there should be more learning from COVID-19, such as the scale of the consequences of supply chain disruption upon which to draw. It would also be useful to understand more about the behavioural aspects associated with supply chain disruption. For example, could climate hazards cause markets to disappear or cause shortages through stockpiling? If CCRA4 takes a more systems-based approach, perhaps this risk would not be assessed as a risk in its own right but considered as part of the food system or economic system as an interconnection between elements of the system. Furthermore, both national and international trade implications should be investigated, including assessments of climate impacts on trade relationships and the nature of trade routes. This should include consideration of international dimensions.

### 6.8 Opportunities for business from changes in demand for goods and services (B7)

Physical climate risks pose a threat to companies operating in the UK, but there are also some business opportunities arising from these impacts, including through shifts in demand for certain goods and services. The CCRA2 Evidence Report found that with sufficient information and climate change expertise, businesses could be expected to respond to market signals and exploit opportunities as they arise. However, the academic literature has only assessed a limited number of opportunities from climate change, mostly related to changing conditions for food and drink production (e.g. growth in the UK wine industry) and therefore the business response suggestion as set out in CCRA2, remains mainly untested. The most significant change has been the growing prominence of climate advisory services in recent years. In general terms businesses that anticipate changing markets may be able to gain an advantage, but various barriers exist that seem to prevent this (e.g. upfront cost barriers to entering new markets, as well as inertia, especially for SMEs), suggesting a role for government intervention to help companies realise these opportunities, similar to measures that have supported businesses to commence carbon management and within the context of developing industrial strategy.

### 6.8.1 Current and future level of opportunity (B7)

Note: it has not been possible to split the evidence by UK country for this opportunity.

#### 6.8.1.1 Current Opportunity – UK wide (B7)

CCRA2 noted that the provision of products and services can be impacted by climate both directly and indirectly through changes in costs or operating expenditure; changes in demand; and through regulatory and other public policy responses. It noted limited evidence of the scope and scale of opportunities arising for companies in the UK and argued that unless prevented by regulation or hampered by low adaptive capacity it could be expected that companies will respond to growing risks and opportunities (Surminski et al., 2016). CCRA2 also warned that the adaptation action of one sector could have negative implications for other sectors or society at large – for example the potential withdrawal of insurance cover, or misguided flood defence investments and small businesses may need support in identifying and realizing opportunities arising from physical climate risks.

Since then, the evidence base has increased (for a summary of methods and approaches see Bonaventura et al., 2018). Earlier studies such as the K-Matrix for BIS (K-Matrix, 2013) fed into UKCCRA2 and have been updated or repeated for example by Ricardo Energy & Environment 2017, who estimated the size of the UK's 'adaptation market' (made up of commercial activities delivering public and private adaptation, flood risk management, research and advisory services) as £1.3bn in turnover with 9,860 jobs. (Ricardo Energy & Environment, 2017). However, these figures should be seen as very preliminary indications, subject to potential double-counting and omission of some adaptation activities, as acknowledged by the report's authors.

Other studies have used business disclosure reports under the CDP to assess the scale of opportunities (see for example Acclimatise for the Environment Agency in 2016). 62% of the market opportunities identified related to increased demand for existing and new products and services (Acclimatise, 2016). From CDP data (CDP, 2018), sectors identifying the highest number of market opportunities were manufacturing (e.g. water efficient products), financial and insurance (e.g. insurance and direct investment in climate resilience), construction, professional, scientific and technical activities (e.g. incorporating climate resilience into new developments and existing infrastructure) and information and communication (e.g. cloud-based computing to promote remote working). In a report based on its surveys, CDP (2019) reported that 225 companies had identified between them US\$236 billion in revenue globally from the provision of adaptation goods and services.

The CCC (2019a) noted a range of current opportunities including in the adaptation goods and services sector with consultancy and adaptation advice; engineering and manufacturing products to manage climate risks; cooling services in transport, construction and real estate, retail and manufacturing; tourism; insurance and other finance products; as well as agriculture, horticulture and food products (see also Chapter 3 (Berry and Brown, 2021) and Chapter 7 (Challinor and Benton, 2021). The extent to which these can be capitalised rest on factors such as: demand response, turnover time, adjustment of product lines, alongside quality and design of products/services,

retraining and restructuring of the workforce, organisational culture and agility. Moreover, most opportunities are coupled with risks or threshold effects, with many parallels to be drawn from the COVID-19 crisis and post-recovery opportunities.

Below we summarize evidence of current opportunities and where possible we report on scale and magnitude of the opportunity.

#### 6.8.1.1.1 Advisory services

There are a wide variety of services being offered to support climate adaptation and risk management. Two European Horizon (2020) projects, MARCO (Market Research for a Climate services Observatory) and EU-MACS (EUropean Market for Climate Services), which included UK case studies, conducted a systematic review. This analysed the current state of affairs regarding the uptake of climate services, assessing the development prospects, and proposing remedies to promote a larger utilization of the development and use of climate services. UK specific examples identified were in the legal sector (e.g. Client Earth, Clyde & Co). Other examples of climate services include providers of adaptation and engineering solutions (e.g. Acclimatise, ICF, AECOM, Arup, WSP), risk assessments and reporting (e.g. ERM, South Pole, Systemiq), climate models and scenario analyses (e.g. PwC, Vivid Economics, Cambridge Econometrics), climate finance (e.g. Mirova, Ortec Finance), climate data (e.g. Moody's, FourTwentySeven, Carbonne 4, CDP, MSCI, Jupiter Intelligence, RMS), climate communications (e.g. Climate Outreach) and climate intelligence (GRI, E3G, Tyndall Centre). Section 7.10 of Chapter 7 (Challinor and Benton, 2021) explores further how the UK is a leader internationally in climate risk disclosure best practices. The recent take-over of Acclimatise by insurance broker Willis Towers Watson underlines the current and future business opportunities in the resilience and adaptation advisory space. Development in risk analytics poses an opportunity for UK companies to lead the market in turning these tools into client offerings with a competitive advantage. The range of efforts to assess and share information about current exposure with investors, regulators and others alludes that current climate risks are beginning to be considered by those providing capital or making investment decisions. In addition, tools that help companies and investors with risk management also are present, such as the Future Fit Business Benchmark. This is a strategic management tool for companies and investors to assess, measure and manage the impact of their activities in alignment with the UN SDG's, available in a public commons license. Professional bodies have also developed guidance that seeks to increase adaptation awareness and integrate into assessments (better addressing opportunities and risks). For example, IEMA published updated guidance in 2020 for the consideration of climate change resilience and adaptation in the EIA process - EIA Guide to: Climate Change Resilience and Adaptation (2020). Guidance has also been developed by the Institute and Faculty of Actuaries, with IEMA as a user guide relating to Climate Related Financial Disclosures.

One example of a service-related opportunity are adaptation standards for businesses. The British Standards Institution (BSI) has developed adaptation standards that companies can use to identify internal roles and responsibilities and demonstrate their adaptation efforts to clients, investors and peers. This can lead to greater recognition and realisation of adaptation opportunities. A summary of recent standards can be found in Box 6.5. Existing standards also hold opportunities for action on Adaptation. The 2015 revised [ISO 14001 environmental management systems standard](#) has many

useful provisions, which include requiring the organisation to consider the wider context and expectations of interested parties, an enhanced focus on leadership and embedding a lifecycle perspective across the value chain. Also, to analyse risks and opportunities and to consider the potential impacts of changing environmental conditions, such as adaptation and climate change impacts. Some organisations such as IEMA have developed guidance to encourage more expansive use of these International Standards to help address adaptation. Many organisations have a form of Management System Standard (MSS) whether based on ISO 14001 or on other ISO standards (e.g. ISO 9001). All ISO MSS are based on the same high-level structure, thus allowing for climate change adaptation issues to be addressed via that MSS's relevant existing standard.

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**Box 6.5 : Climate Change Adaptation Standard. Source: Communication from BSI Group during CCRA3 stakeholder engagement.**

BSI (British Standards Institute) are the UK's National Standards Body, creating documents of good practice for industry. In July 2019 BSI produced the first adaptation to climate change standard: 'ISO 14090 Adaptation to Climate Change, Principles, Requirements and Guidelines'. This sets out actions for any organisation to create a plan or to enhance its plan for climate resilience and was led by Civil Engineer, John Dora. BSI are currently working with ISO (International Standards Organisation) to create a document on using ISO 14090 as part ISO 14001 'Environmental Management Systems' (the most extensively used environmental standard in the world with over 17,000 certifications in the UK – recommended by agencies such as the Environment Agency).

As a wider part of the BSI programme of work on climate adaptation BSI are working with ISO on the preparation ISO 14091 on impacts, risk and vulnerability for adaptation (due to publish Q1 2021) and ISO 14092 on climate adaptation for local authorities. BSI themselves have started work on a standard on adaptation pathways – a decision making process for short to long term and at any stage (due to publish Q2, 2021). All of these pieces of work have included contributions from organisation such as the CCC, Defra, HS2, Mott Macdonald, Anglian Water, Atkins and many others.

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structure, thus allowing for climate change adaptation issues to be addressed via that MSS's relevant existing standard.

#### 6.8.1.1.2 Retail

For the retail sector increased sales of seasonal garments in the retail sector were noted when significant temperature change occurred (Bahng, et al., 2012). However, the increased variability in weather means production lines and global retail supply chains have to be better equipped to respond to change quickly, as discussed in Risk B6. Thus, projected retail opportunities may be hard to capitalise, particularly for small businesses who may be operating under just-in-time manufacturing and are unable to diversify production (PwC, 2015). Set against this economic opportunity, reports such as the enquiry in 2019 by the Environmental Audit Committee have recommended against escalating consumption, especially in terms of waste impacts and called for an Extended Producer Responsibility scheme for textiles, stronger eco-design principles and clear incentives for design for recycling, design for disassembly and design for durability. Weather variability as an additional demand consideration for seasonal garments may be addressed and considered within this broader context of sector sustainability.

#### 6.8.1.1.3 Food and drinks

The sector has identified opportunities from reductions in water usage, as highlighted by the Food & Drink Federation's challenge to its members to reduce water usage by 20% by 2020, with British Sugar reducing water usage across its operational activities by 26% (FDF 2019).

#### 6.8.1.1.4 Finance

In the finance sector there are opportunities linked to the sustainable finance and ESG agenda, including improved credibility and potential for market leadership, competitive advantage through early adaptation and being first movers, attracting clients and talent aligned to climate objectives and improved reputation (UNEP-FI, 2016). These opportunities are supported by studies, for instance, Deloitte EIB and Global Alliance for banking with values (2019) find that banks with good performance on material ESG issues outperform banks with bad performance on the same issues by more than 2%. Adaptation and resilience investment opportunities (discussed in B4) are growing but there are still few examples of realising those through innovative financial instruments (see for example Climate Bonds Initiative 2019 or GCA 2020).

In terms of specific product opportunities CCRA2 highlighted the insurance sector and identified three key opportunities: new insurance products, methodologies in flood insurance and British insurers scoping business opportunities in emerging markets with little insurance penetration (Surminski et al., 2018). Such opportunities continue to exist. New tools include parametric insurance for extreme weather events (Mercer 2018; Horton, 2018) which has the potential to avoid the incongruities of legal liability to climate change and is a promising alternative to loss-based insurance, especially because of the additional advantage of predictability. In addition, market opportunities for catastrophe bonds and resilience bonds are growing. There is also the potential for insurance to be used as a catalyst for government planning, as climate risk information from



insurance processes can support public sector anticipatory climate risk management, including loss prevention and adaptation (Surminski, Barnes and Vincent, 2019). There is also a promising partnership opportunity between the UK public and private sector on flood insurance, as increased partnership beyond just the national government and industry can help reduce flood risk and maintain affordable insurance premiums (Crick, Jenkins and Surminski, 2018).

#### 6.8.1.1.5 Construction

Across the UK, there is evidence of further opportunities in the construction industry as businesses change their premises to adapt to climate change. This provides an opportunity for an increase in repairs, maintenance or clean-up contracts. For example, Northern Ireland has guides on their government website for the potential of entirely new projects and services, such as improved waste management or preventing soil damage during construction projects (Northern Ireland Business Information, 2019). This opportunity however will be set against impacts on public sector bodies who will face associated increased costs (for example within the NHS and Local Authorities). One further example identified in UKCCRA3 stakeholder engagement is urban green infrastructure and its provision and maintenance, such as green roofs, urban tree planting, park expansion and maintenance to maintain quality. Examples of value benefits within the UK have been recorded by tools such as the Greenkeeper project (Greenkeeper, 2020). However, how these opportunities are being realized by businesses is unclear.

#### 6.8.1.1.6 Heritage sector

For the heritage sector increasing temperatures and extreme weather events intensify the need for repair and maintenance of heritage sites. Therefore, more will need to be spent on the materials industry (sandstone, slate etc) and on sector-specific skills (employees to repair traditional/historic buildings). As an example, an estimated £1.2bn (including grants) was spent on repairing and maintaining the historic environment in 2017 and private investment accounts for three quarters of all funding. At present, some bodies like COVID Historic Environment Resilience Forum (CHERF) are facilitating rebuilding, recovery and resilience opportunities. The industry supports 66,000 jobs (as per 2017 figures), and the skills investment plan for Scotland's Historic Environment accounts for new job creation (Historic Environment Scotland, 2019). Nonetheless, there are critical barriers that prevent these opportunities from being realised. For instance, rebuilding requires particular skill sets and thus, industry-wide retraining may be required. This may create bottlenecks and delay overall reconstruction response. Many businesses operate out of heritage assets such as traditional buildings and/or rely on heritage-driven tourism. Income loss due to COVID –19 and the lockdown may lead to further delays in addressing climate risks.

#### 6.8.1.1.7 Agriculture

Opportunities for the agriculture, forestry and marine sectors are outlined in Chapter 3 (Berry and Brown, 2021). Recent evidence shows that many Northern Ireland farms have diversified, expanding business into other crops they do not currently grow and using land for business activities beyond traditional farming (Northern Ireland Business Information, 2019). New business activities can include energy or non-food use crops such as crops grown to generate heat and electricity or to

produce transport biofuels (Defra, 2013). The Nordic Development Fund (NDF 2020) identifies a range of opportunities for climate resilience products in agriculture (Box 6.6).

**Box 6.6: Opportunities for suppliers of climate resilient products in agriculture. Source: NDF, 2020.**

A report from the Nordic Development Fund (NDF) (2020) highlights that there are numerous opportunities for climate resilient products, services and technologies in private markets. Whilst most companies are not capitalising on this opportunity, those that are providing adaptation products/services are gaining a competitive advantage.

For instance, in the agricultural sector, most innovative resilience services are coming from small businesses. Moreover, businesses that have incorporated adaptation in their business models are best able to respond at the local scale. However, specific adaptation technologies and agricultural equipment are still being provided by large corporations.

NDF identify key barriers faced by suppliers of climate resilience products:

- Factors affecting business growth:
  - Limited access to credit and financial support.
  - Difficulties in proving a business case for individual products or services.
  - Difficulties in communicating instructions or product specifications to end users.
  - Regulatory, tax and financial frameworks are not sufficient to provide support for small businesses.
  - Limited support for innovation.
  - Constantly changing international standards.
  -
- Climate specific factors:
  - High 'switching' costs and risks in transitioning from existing practice to climate-resilient practice.
  - Limited integration of climate change into regulation.
  - Lack of incentives for addressing resilience.
  - Poor awareness of climate-change impacts as a business opportunity.
  - Final users are not aware of, or interested in, climate solutions and prioritise more urgent risks.
  - Difficulties in predicting climate risks accurately and quantifying future impacts in financial terms.

Addressing these challenges will expedite adopting opportunities in the agricultural sector, and specifically help SMEs. SMEs have been identified by NDF as leaders in climate resilient products, most likely to be adopting adaptation solutions and selling climate products to others.

### 6.8.1.2 Future Opportunity - UK wide (B7)

A number of possible opportunities for new or expanding sectors are known by stakeholders, but there is little or no literature available quantifying the size or potential future for these industries. Stakeholder engagement in the course of the UKCCRA3 project noted future opportunities for rural land use industries, such as afforestation, peatland restoration, on-farm reservoir creation and maintenance, paludiculture, different types of agricultural diversification. And there may be significant opportunities in the UK energy sector in the next 5 years as discussed in the UK'S Draft Integrated National Energy And Climate Plan (NECP government document) 2019 (BEIS).

#### 6.8.1.2.1 Food

As highlighted in section 7.4 of Chapter 7 (Challinor and Benton, 2021), climate change impacting global patterns of food production could create need opportunities from imports and/or exports. It is important to assess agriculture in the context of trade effects, not just productivity – a recent PESETA 4 publication (2020) shows the UK benefits. In addition, IIASA modelling work with GLOBIOM finds any negatives are reduced considerably as a result of market adjustments due to more severe climate change impacts on agriculture outside Europe. Changing the type of seafood available within UK waters through wild capture fisheries, via potential changes in species and distribution within the fishery. In addition, there is an opportunity to increase productivity of the fishery through enhanced production at higher latitudes (Garrett et al., 2015). Within the seafood industry, opportunities could arise in wild capture fisheries, from potential changes in species and distribution and the productivity of the fishery, e.g. enhanced fisheries production at higher latitudes (Garrett et al, 2015). More information on opportunities within the seafood industry is found in Chapter 3 (Berry and Brown, 2021).

#### 6.8.1.2.2 Tourism

Further opportunities might arise from extending the local tourist season due to warmer summers: there are numerous studies that show in Northern European regions and the British Isles, tourism activity increases from climate change (for beach and summer tourism) could lead to limited and localised economic benefits (e.g. Perrels et al., 2015)<sup>15</sup>. Barrios and Ibañez Rivas (2013) used a travel cost approach and hedonic valuation of recreational demand and amenities in a scenario of approximately 4°C global warming at the end of the century<sup>16</sup>. They estimated that in Southern EU Mediterranean countries, that climate change scenario would lower tourism revenues between - 0.45% and -0.31% of GDP per year. In contrast, in Northern European regions and the British Isles, tourism activity could lead to benefits, with the British Isles gaining +0.3% of GDP per year respectively. However, the impacts depend on whether holiday duration and timing are fixed, or whether there is a redistribution to shoulder seasons. If these adaptations occur, the gains to the UK fall, to 0.2% of GDP if tourists change duration, and gains are negated if tourists change duration and timing. Clearly any economic benefit that is identified, will have to be transparently communicated

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<sup>15</sup> Tourism is a major business in the UK and there are many subtleties associated with climate change and tourism. We therefore recommend further work in this sector.

<sup>16</sup> ECHAM5 climate model with the SRES A1B scenario

within a broader and balanced explanation of the extensive costs to the economy and society from the changing climate.

#### 6.8.1.2.3 Digital innovation

Digital innovation plays a key role for businesses (Power et al., 2020). There is an opportunity for in-house climate data analytics within businesses, as firms are increasingly adopting scenario analysis for risk management, investment decisions, and identification of investment opportunities (Mercer, 2019) in response to the growing ratings risk posed by climate change (Economist, 2019). With the abundance of data and the rapid development of predictive modelling, decision-making based on algorithms has potential to change the way businesses view, understand, and analyse risks, as well as adopt adaptive behaviours (Ford et al., 2016). Algorithmic modelling and big data are perceived as a promising way to support climate change adaptation and can reduce research costs for businesses (Huntingford et al., 2019). Businesses increasingly rely on algorithmic reasoning for decision-making, such as using artificial intelligence to process large datasets to discover historical weather patterns, optimise climate forecasting, predict early crop yield or crop issues, and real time disaster risk mapping. Water companies are exploring these technologies applied to smart metering or analysing demand and consumption trends. Nonetheless there are caveats to this. For example, artificial intelligence (AI) early disaster warning systems are trained using historical data on weather patterns, but there is a lack of understanding of future model predictions. This could result in false or negative alarms (Sakata, 2018). To ensure AI is used responsibly, government and industry leaders need to work closely to use its potential to aid corporate decision-making. Frameworks for decision-making under uncertainty suggest that it can feel rational to delay significant and irreversible investment (Agrawala et al., 2011), but if evidence generated through AI or otherwise shows that benefits will eventually be accrued, this supports a business case for investing in adaptation.

#### 6.8.1.2.4 Shipping

A nascent literature is identifying opportunities for shipping, for example, UKCP18 identifies that average significant wave height may reduce under climate change, which could improve access windows for safer at-sea working (Palmer et al., 2018). Further insights from the UKCP18 projections can be found in Chapter 4 (Jaroszweski, Wood and Chapman, 2021). In addition, the shipping industry could see large fuel savings and associated reductions in greenhouse gas emissions by using transit shipping through the Arctic (Masselink et al., 2020) – this is covered in the risk analysis in Chapter 7 (Challinor and Benton, 2021). As highlighted in Section 7.8 of Chapter 7 (Challinor and Benton, 2021), due to the construction and launching of the RSS Sir David Attenborough the UK maritime sector is now well-placed to advise the rest of the world on how to implement the Polar Code (mandatory requirements relating to the operation of ships in polar waters).

#### 6.8.1.2.5 Wine

Some UK-based work has been done on the current and future opportunities provided by the UK wine sector (Box 6.7), but no analysis of the potential future size of the opportunity has been found for other sectors in the literature. New opportunities for UK growers can arise both from changes in UK climate as well as from deteriorating conditions for wine growers in other regions across the

world, making wine production in the UK more viable. See Chapter 7 (Challinor and Benton, 2021) for international issues.

**Box 6.7:** Opportunities for the UK Wine Sector. Source: CREWS-UK (2021); Nesbitt et al., 2021, 2018, 2016; Gannon et al., 2021a; Watkiss et al. 2019.

Watkiss et al., 2019 reported that:

- There is no specific policy objective for English wine production, and this was not identified in the Government's National Adaptation Programme.
- However, in 2016 the English Wine Round Table with the Wine and Spirit Trade Association and Defra made pledges to increase the hectares of vineyards from 2,000 to 3,000 ha by 2020, and to increase wine production to reach 10 million bottles in 2020, with the ambition that 25% of this would be exported, generating £30 million in export revenues (WSTA, 2016). Looking further, Wines of Great Britain has estimated that in 2040 annual production could reach 40 million bottles (WGB, 2018).
- The analysis quantified the potential benefit of ~£50Million/yr by the 2050s but only if climate variability is addressed in planning by growers and local authorities.
- There are high potential economic benefits from creating enabling environment and enhancing uptake of low regret adaptation, with high benefit to cost ratio.

The CREWS (Climate resilience in the UK wine sector) Report offers the following insights:

- Viticulture in the UK expanded 370% (761 to 3579 hectares (ha)) between 2004 (when sparkling wine started to dominate production – Nesbitt et al., 2016) and 2019 (WineGB, 2020a) (Nesbitt et al., 2021).
- Growing season average temperatures (GSTs) in the main UK viticulture regions have warmed ~1°C between the 1981-2000 and 1999-2018 periods to a recently more consistent >14°C GST (Nesbitt et al., 2021). This warming underpins the recent rapid growth of the UK wine production sector and its dominant focus on sparkling wine varieties, described by producers in Gannon et al., (2021a): "we can ripen grape varieties that we couldn't ripen 20 years ago... we couldn't make the wines that we are making today, 20 years ago".
- The sector's market capacity remains unclear. However, where viticulture investment is sought, the potential already exists to further develop prime vineyard land, predominantly in southern and eastern England (Nesbitt et al., 2016; Nesbitt et al., 2018).
- The very nexus that facilitated the introduction and current 'success' of dominant varieties in the UK – climate change – may continue to provide opportunities for further varietal or wine style change. Nesbitt et al., (2021) model near term (2021-2040) trends and variability in the vine-growing season, using the latest high-resolution (2.2km) ensemble of UK climate change projections (UKCP18) for the UK. In this analysis:
  - o Growing Season Temperatures (GST) are projected to increase by a further 1-2.5°C.
  - o Significant areas within Eastern England, the Midlands, south-central and south-eastern England are projected to have over 50% of years, during 2021-2040,

within the range of growing conditions that led to a bumper UK grape harvest in 2018.

- o Top vintage Champagne 'conditions' are re-produced in English sparkling wine producing areas more consistently and new areas of suitability are projected to emerge.
- o Growing season temperatures from 1999-2018 in Burgundy (France) and Baden (Germany) in high quality vintage years within that period, when projected over the UK for the next 20-years as a climate analogue, cover large areas in southern and eastern England, suggesting potential for still Pinot Noir production in the near-term.

### 6.8.1.3 Lock-in and thresholds (B7)

#### 6.8.1.3.1 Are there lock-in risks? (B7)

There is a risk of lock-in related to land use change to take advantage of new forms of food production. For example, land-use change for new wine production needs to consider the changing climate when considering varietal choice for new planting as it involves high capital investment and the payback time for wine is longer than for many other agricultural crops due to the time needed for vines to mature (Watkiss et al., 2019). The risk of lock-in emphasises the urgent need to increase adaptation action now, even in the short-term (Watkiss et al., 2019). There are risks of lock-in additionally from potential poor soil management due to lack of crop rotation or reliance on particular varieties.

The CREWS-UK project (CREWS-UK, 2021) highlighted examples of lock-in within established viticulture landscapes, limiting adaptive capacity (Gannon et al., 2021b). Certain adaptation options, including the decision of where to plant vines and which varieties and rootstock to plant – notably adaptation options which are often held to have some of the highest adaptation potential (Nicholas & Durham, 2012; Watkiss et al., 2019) – require much larger investments in terms of finance and effort within established vineyards and thus produce intransigence within viticultural landscapes when climate risk is not incorporated into vineyards' initial design. Cultural and economic factors shape this intransigence, including through marketing decisions. For example, the world's most famous wine regions are often associated with a very small number of varieties, concretised in protected designations of origin (PDO). Analysis in Gannon et al., (2021b) suggests the young, and much less established UK viticultural landscape has much greater flexibility, to establish development trajectories that account for changing climate risk. Yet, the authors also identify multiple ways in which the UK landscape is reproducing patterns of lock-in seen in more established viticultural regions, for example through sector concentration on a limited range of grape varieties in sparkling wine production and through regulatory structures, including PDOs.

As discussed in the case of opportunities in retail and consumer spending, there are also risks locking in to mal-adaptative products and services, such as air conditioning. Moreover, business as usual responses to changing demand for services, such as seasonal clothes, without identifying climate

change as a risk driver, compromises production line's ability to respond to weather variability or extreme weather events.

#### 6.8.1.3.2 Are there potential thresholds? (B7)

There are a very large number of potential opportunities, each with particular threshold effects, either in terms of biophysical thresholds (e.g. thresholds for suitability for new crops, comfort levels for beach tourism), but also potential investment return thresholds, when it makes sense for the private sector to enter and scale-up.

Watkiss et al., (2019) found studies projecting that 2°C global warming would change England into an 'intermediate climate' wine region, i.e. a major positive outcome compared to the current climate (Georgeson and Maslin, 2017). Extrapolating further, 4°C of warming could make England into a 'warm' wine region. Therefore, while climate change could open a range of opportunities for growing different varieties of grapes which are currently cultivated in Europe, the level of warming will affect the type of opportunity. Further, there are likely to be a number of other threshold effects: while there is likely to be a fall in lower temperature threshold levels for wine growing, possible threshold risks are identified around water availability, and the temperature suitability ranges (and heat limits) for some current colder temperature wines. There is potential for inter- and intra-annual temperature and precipitation variability to increase under climate change (Beniston et al., 2007; Fraga et al., 2013). Moreover, warmer spring temperatures are advancing the grape-growing season, with earlier bud burst bringing the period of time that vines are vulnerable to frost-risk forward in the year (CREWS, 2020). Weather thresholds are suspected to have similar effects in the case of tourism and leisure and recreation opportunities.

The ClimateWise physical risk study (Westcott et al., 2020) shows that the effectiveness of adaptation measures such as property level protection decreases once certain temperature degree thresholds are reached – pointing out that there are limits to adaptation and that action now is required to keep risks at a manageable level.

#### 6.8.1.4 Cross-cutting risks and inter-dependencies (B7)

The opportunity for business from changes in goods and services depends on consumer demand and business ability to respond to this. Consumer demand may be hampered by climate impacts – for example for location specific services, such as tourism, where flooding (Risk B1) and coastal erosion (Risk B2) at sites might hamper the size of the opportunity. Moreover, business capacity to respond to food and agriculture opportunities are constrained by water scarcity (Risk B3) and supply chain (Risk B6) risks. The inability for supply chains to respond to shocks and changes in demand has been noted in the COVID-19 crisis response (WEF, 2020).

In some cases, opportunities may encourage maladaptation – such as the increased supply of air conditioning cooling products, which could exacerbate long-term climate risk. This was considered in the case of air conditioning units in Risk B5. Moreover, short-term opportunities in reconstruction are far outweighed by the infrastructural damage of extreme weather events and associated lost

business revenue streams. This is seen in the case of heritage tourism sector, where frequent site damage threatens overall firm survival, despite short-term job creation.

Opportunities also depend on the macroeconomy. For instance, recession, employment loss and health risks post-COVID-19 could limit opportunity realisation. This is especially true for the climate advisory sector, as demand for services may fall in cash-strapped sectors and amongst SMEs. Ultimately, increased variability of extreme events and longer-term climate impacts mean most opportunities depend on numerous factors in order to be realised.

#### 6.8.1.5 Implications of Net Zero (B7)

Business opportunities related to climate resilience will have to be aligned with the UK's path to Net Zero. The scope for increased summer tourism, for example, will have to account for the carbon footprint of tourists. Similarly, the growth in wine making will have to be embedded into a wider strategy for reducing land use-related greenhouse gas emissions. There may be business opportunities in design and deployment of zero-carbon flood resilience solutions (Risks B1, B2) and the design, manufacturing, installation and maintenance of zero-carbon cooling technologies (Risk B5).

There may also be business opportunities arising from the need to make Net Zero solutions climate-resilient, which may have implications on their design. Sometimes this creates synergies (e.g. nature-based solutions) and sometimes it might create trade-offs for example energy efficiency vs overheating in the case of low-carbon retrofits (as suggested by the CCC, 2020a).

#### 6.8.1.6 Magnitude scores (B7)

The magnitude scores (Table 6.25) are based on expert judgement and anecdotal evidence for the scale of current and future opportunities. The magnitude of this opportunity is expected to increase however there are likely to be thresholds (adaptation limits) such as with higher warming scenarios such as 4°C by the end of the 21<sup>st</sup> Century. A range of UK-wide sector-specific opportunities are discussed in the literature, the size of which varies based on the sector, but little quantification. Hence there is low confidence across magnitude scores.



**Table 6.25** Magnitude scores for opportunities for business from changes in demand for goods and services.

Country	Present Day	2050s		2080s	
		On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century	On a pathway to stabilising global warming at 2°C by 2100	On a pathway to 4°C global warming at end of century
<b>England</b>	Low	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Northern Ireland</b>	Low	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Scotland</b>	Low	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)
<b>Wales</b>	Low	Medium	Medium	Medium	Medium
	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)	(Low confidence)

## 6.8.2 Extent to which the current adaptation will manage the opportunity (B7)

### 6.8.2.1 Effects of current adaptation policy and commitments on current and future opportunities (B7)

#### 6.8.2.1.1 UK-wide

Given the low level of understanding of the opportunities to businesses from climate change, and the likely barriers to small businesses in particular to enter new markets, there is likely to be a role for Government in providing evidence and supporting businesses to transition to new functions as the climate changes.

An example of this is the UK's 'resilience offer', which is promoted internationally across a range of sectors (e.g. in finance, infrastructure), aiding other countries' efforts to increase their own resilience to the effects of climate change. UK Export Finance is, for example, working with the Environment Agency and OGDs to develop a UK offer in the Climate Resilience space, specifically, in the area of Flood Control Risk Management (FCRM). This work is focussed on the internationalisation of a domestically-focussed supply chain. This remains a work in process, with the aim of producing a UK FCRM supply chain and export finance prospectus in 2021.

The Department for International Trade (DIT) is working across government to influence policymaking and ensure UK businesses and the City of London can capture opportunities and demonstrate leadership in finance and insurance, including through the Global Resilience Summit in 2021. DIT will promote a consolidated resilient infrastructure offer (e.g. resilient infrastructure offer in water; G2G campaigns; linking UK firms with international partners to deliver infrastructure in third countries).

The Government's UK Industrial Strategy also does not reference climate change adaptation and it is left up to the industries who could benefit from climate change to consider the opportunities. The CCC (2019a) concluded that further research is needed to understand the size of direct and contributory climate-related business opportunities across the UK. They also recommended that BEIS should set clear deadlines for ensuring listed companies and large asset owners report on climate-related risks and opportunities, as recommended by the Green Finance Taskforce and Environmental Audit Committee (see risk B5 above). This should include committing to new legislation if reviews find that the quality of reporting does not improve.

Similarly, the Government's 2019 Green Finance Strategy provides an opportunity to direct more finance towards adaptation and develop new adaptation products and services but does not provide a detailed plan on how to stimulate the adaptation economy, which is lagging behind growth in other countries (UNEP, 2018; Georgeson et al., 2016). The Budget announced in March established a £10 million Natural Environment Impact Fund to help prepare green projects that could be suitable for commercial investment in order to encourage private sector support for environmental restoration, including climate adaptation benefits.

#### 6.8.2.1.2 England

The CCC (2019a) found that there is no overarching plan in the second National Adaptation Programme (Defra, 2018b) to support businesses to realise the opportunities from climate change. Local Industrial Strategies (LIS) do mention climate related action, but not in the specific context of the reduction of climate risk driving economic policy. For example, the North East Local Enterprise Partnership responded to inquiries about climate action following their July 2019 strategy summit, stating that the priority focus for LIS continues to be productivity, but there is work focused on North East's opportunities to invest into decarbonisation and wider climate related action. In addition, the North East Strategic Economic Plan does recognise the need to tackle climate change and promote clean growth (NELEP, 2019). Another example of this is using natural capital in a Local Industrial Strategy (LIS) to protect infrastructure from climate risks, such as flooding, drought and extreme temperatures, to secure industrial supply chains against climate-induced shortages of raw materials, and to provide uninterrupted supplies of water to industrial water users (Rural Enterprise UK, 2019).

#### 6.8.2.1.3 Northern Ireland

Northern Ireland has a free service offered by Invest Northern Ireland – the government’s official online channel for business advice and guidance, including a dedicated information guide on how to “Adapt your business to climate change” (NI Business Info, 2020). This guidance offers best practice advice on why Northern Ireland businesses should adapt to the effects of climate change. It highlights the risks and opportunities that could result from climate change and how businesses can manage these. Helpline numbers and external links signpost local businesses from the online guidance to the relevant experts, including government departments and business support organisations, who can assist them. In 2019-20, customers made 12,500 views of climate change adaptation and prevention guidance on nibusinessinfo.co.uk. The ongoing maintenance and development of this guidance ensures the communication of key future changes and the highlighting of climate-related support to Northern Ireland businesses. The site is a channel for communicating climate adaptation support and business-related initiatives via its Business News section, Events Finder, Business Support Finder, monthly newsletter and social media channels.

#### 6.8.2.1.4 Scotland

In April 2018, ClimateXChange published a paper on ‘Scoping and Sizing the Scottish Adaptation & Resilience Economy: An overview of methods’ (Bonaventura, 2018). This paper made recommendations on how to progress the scoping and sizing of the ARCC economy in Scotland, by establishing a baseline assessment of the Scottish A&RCC Economy and developing a method to support periodic updates to the baseline dataset. The newest Scottish Adaptation Programme published in 2019 (SCCAP2) includes a sub-outcome on business opportunities from climate change. Included under this theme is the provision of guidance for businesses to be climate-ready, though it is not known how this has yet translated into a change in the size of the adaptation economy in Scotland.

#### 6.8.2.1.5 Wales

Welsh Government’s climate adaptation plan, Prosperity for All: A Climate Conscious Wales includes a theme for ‘successful businesses’ and sets out multiple actions to support businesses in understanding climate risk and adaptation. This includes plans to review and republish its current Climate Change Business Adaptation tool. No references are made to support business in finding opportunities from climate change, however revision of the adaptation tool may prove to be a useful channel to do this. Post-EU exit support in Wales includes farm payments as outlined in the ‘Sustainable Farming and Our Land’ document, and this support based around sustainability will support farm income and rural economies while delivering interventions in land management to support climate resilience. Landowners seeking support must now enter into an ongoing dialogue with Welsh Government and commit an approach that is built firmly on the principles of collaboration – while progress in reducing carbon footprint is part of this agreement, adaptation will be an important part of farm business development for the future and Welsh Government intends to provide a range of support for that purpose via the proposed new scheme. The Welsh Government also includes actions to maximise adaptation benefits in the design of the ambitious plan for a National Forest in Wales as well as encouraging farmers and other land managers to plant

new areas of woodland through the Woodlands for Wales Strategy, and to identify opportunities for housing retrofits as part of efforts to decarbonise the housing stock. The Welsh Government is researching land suitability through their CSCP09 report, and sustainable development principles guide the fisheries post-EU exit strategy as well.

#### 6.8.2.2 Effects of non-governmental adaptation (B7)

Overall one can argue that it is down to individual businesses to identify, assess and realize business opportunities. However, there is evidence (Watkiss et al., 2019) that Government can support this by creating an enabling environment. Public private partnerships could play a significant role in supporting corporate adaptation. This was recently investigated by the ESRC-funded 'Place-based Climate Action Network' (PCAN) which is working with businesses in city-specific, cross-sector Climate Commissions across several cities in the UK. The Commission aims to catalyse the projects and partnerships that reduce carbon emissions and increase climate resilience in a way that is tailored to particular locations with their mix of physical and economic geography, cultural and historical legacy, and demography. Business activity in city commissions can be concerned with improving operational efficiency and risk profiles, future-proofing existing activity, creating new products and services for new markets, or, often, a mixture of all of these. Developers– like Citu and CEG in the Leeds Climate Commission and CCG in the Edinburgh commission – are seeking to reduce the energy costs associated with new projects, but also to be part of creating a city-wide demand for low energy and resilient housing, whilst collaborating with infrastructure providers and public sector agencies. Privately Owned Public Utilities are well-represented in local Commissions, with water companies (e.g. Yorkshire Water), gas network operators (e.g. Northern Gas Networks) and electricity providers, exploring their role as incumbents in a system undergoing rapid change. Professional services firms in law and finance are also engaged with city commissions, often seeking ways to deploy more locally expertise gained internationally, such as green bond issues or private wire supply agreements (PCAN 2020).

#### 6.8.2.3 Is there an adaptation shortfall? (B7)

From the available data it is not possible to tell the extent to which UK businesses are identifying and realising the opportunities from climate change. The lack of data on business opportunities suggests that opportunities may be limited and/or not being recognised by businesses. For instance, Deloitte et al., (2019), recognise that not all ESG issues matter equally for financial performance, and the relevance and opportunities vary depending on the sector and firms in question. There are also gaps in sizing the potential size of the adaptation goods and services sector across the UK and separately for each administration.

#### 6.8.2.4 What are the barriers preventing adaptation to the opportunity? (B7)

In our view there is still a large awareness gap and limited technical understanding of climate opportunities. Although climate change awareness overall is growing, the business sector is currently dominated by short term concerns around EU exit and COVID-19. Medium- and longer-term risks are overlooked and could benefit from Government prompting.

## 6.8.2.5 Adaptation scores (B7)

<b>Table 6.26</b> Adaptation scores for opportunities for business from changes in demand for goods and services.			
<b>Are the opportunities going to be managed in the future?</b>			
<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

## 6.8.3 Benefits of further adaptation action in the next five years (B7)

## 6.8.3.1 Additional planned adaptation that would address the adaptation shortfall? (B7)

Identifying opportunities in increased demand for goods and services, such as climate advisory or adaptation products are important to make a business case for climate adaptation in the next five years. This requires greater evidence, such as case-studies, and further investigation into emerging sectors. Currently, there is low confidence in information available, and some opportunities, such as in the retail sector, require further investigation. Business capacity needs to be assessed post-COVID-19, to determine whether these opportunities will be realised, and what barriers exist.

Across the country there appear significant opportunities linked to retro-fitting of the building stock. Most initiatives such as the smart energy programme, are currently aimed at achieving low-carbon targets. Using these investments to also increase climate resilience of buildings would bring employment and profitability to construction and advisory services.

Opportunities in some sectors, like increased use of air conditioning due to hot weather, must be reassessed, especially in view of lock-ins, maladaptation, threshold effects and associated transition risks, such as changes in energy policy.

In view of COVID-19, a greater emphasis must be placed on transformational adaptation, and the opportunities this brings (Tompkins et al., 2010; UKCIP, 2015). Changes in demand for goods and services must be viewed in tandem with sectoral change, technological advances and the institutional and labour-market changes. The emphasis placed on 'green stimulus' presents government-backed demand in sectors. Whilst the UK currently ranks highly in the 'Green Stimulus Index', this is largely due to underlying environmental performance.

There are also some new opportunities in transport, industry and energy (Vivid Economics and Finance for Biodiversity Initiative, 2020). Opportunities for financial investments have also been identified. However, it remains to be seen whether there is industry-wide demand for adaptation solutions (Vivid Economics and Finance for Biodiversity Initiative, 2020).

Further investigation is required into the regulatory and institutional networks that can facilitate these opportunities. The LSE Climate Risk Business Survey (2020) found that respondents engaging

with suppliers, regulators, banks, investors and insurers are undertaking a more diverse range of adaptation actions. It remains to be seen whether recommendations for investment in adaptation technologies presented by the CCC (2020) or expert calls for a Sustainable Recovery Alliance (Allan et al., 2020; Hepburn et al., 2020) proposed to the Government will occur and produce benefits.

#### 6.8.3.2 Indicative costs and benefits of further action (B7)

Given the range of sectors and opportunities it is difficult to identify specific costs and benefits of adaptation. There are sectors where analysis has been undertaken (e.g. Watkiss et al., 2019 for wine) which indicates that under a scenario where wine growers were able to realise the benefits of climate change due to better information (and appropriate response), and at the same time introduce adaptation measures to address potential variability risks, there would be very large economic benefits, and a high benefit to cost ratio.

#### 6.8.3.3 Overall urgency scores (B7)

<b>Table 6.27</b> Urgency scores for opportunities for business from changes in demand for goods and services.				
<b>Country</b>	<b>England</b>	<b>Northern Ireland</b>	<b>Scotland</b>	<b>Wales</b>
<b>Urgency Score</b>	Further investigation	Further investigation	Further investigation	Further investigation
<b>Confidence</b>	Low	Low	Low	Low

Note: The urgency score is based on expert judgement due to lack of quantified analysis. The magnitude of this opportunity is expected to increase however there are expected to be thresholds (adaptation limits) with higher temperature increases such as 4°C global warming. Overall, the costs and benefits of adaptation solutions are likely to vary on a case-by-case basis, and this is one area where the evidence base is especially low and would benefit from more investigation over the next five years.

#### 6.8.4 Looking ahead (B7)

Looking ahead, more evidence is required for CCRA4 on business opportunities. Most case-studies available merely present a superficial overview of short-term demand for products/services, without commenting on opportunity realisation and business capacity to respond. Academic evidence in particular, is lacking, and further investigation is required to assess the robustness of findings in this section. The reliability of sources and validity of claims made in the grey literature require further investigation.

Opportunities must be systematically linked to the business and institutional capacity for realisation. Opportunities arising from the COVID-19 recovery requires particular attention. Longevity of

demand for goods and services must be considered, as well as the demand variability (e.g. fluctuation in seasonal retail sales).

Importantly, any opportunities should be viewed in tandem with the risks they are arising from. Benefits must be weighed alongside the larger-scale costs and damages involved. Evidence on climate risks must extend its reach beyond governmental institutions by working co-productively with businesses. Such inclusivity is paramount to promote more robust evidence-based local climate adaptation strategies where different approaches are needed for identifying risks and how these risks affect different decision-makers (Howarth et al., 2020).

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## 6.10 APPENDIX

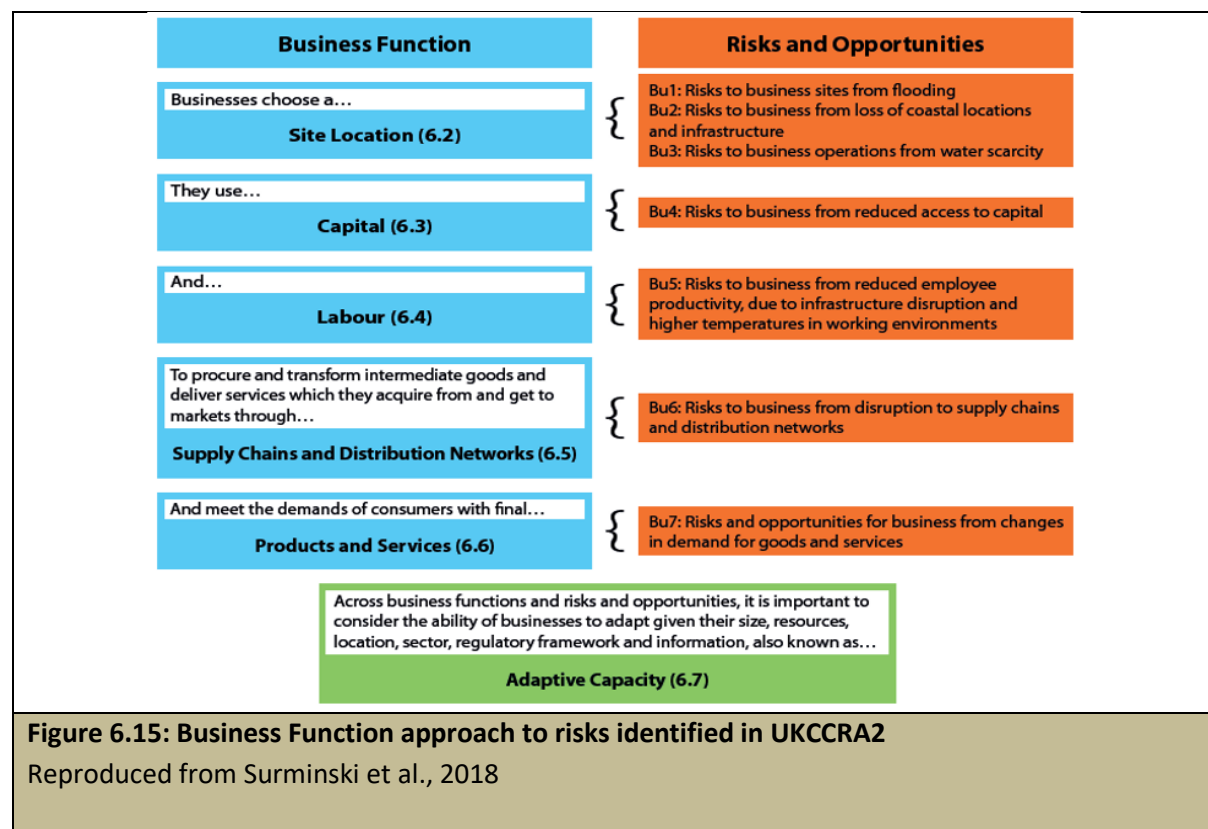
### The Business function approach

We apply a business function approach as per CCRA2 to investigate if and how climate impacts can disrupt current business practices or create new opportunities across six key business functions.

These functions are:

- **‘Access to capital’** business function reflects on the implications for access to finance, including insurance, loans, investor relations and credit ratings.
- **‘Distribution’** function is referring to logistics, which includes utilities and transport infrastructure. ‘Distribution’ addresses the downstream side of the production process and business interaction, in other words, the ways in which finished products and services are distributed across customers and markets.
- **‘Employees’** looks at the implications for workforce in terms of working environment and recruitment. It also refers to aspects related to customers’ and suppliers’ comfort as well as changing lifestyles and social trends. Labour productivity is an important aspect in this context.
- The **‘products and services’** business function refers to the business area of markets and processes. Markets include the changing demand for goods and services as well as altering consumer behaviour. It also takes into account emerging markets for new products and the early movers’ perspective in developing products and services. The function also incorporates impacts on production processes and service delivery under given regulation. In other words, products/services look at economy-wide aspects, rather than firm specific. It includes markets and the structure of the economy.
- **‘Site locations’** refers to the way in which buildings and site properties are designed, constructed and maintained, as well as how these facilities are managed. It considers how the choice of location drives climate risks and opportunities.
- **‘Supply chain’** covers the upstream part of the production process as it refers to searching and extracting materials and resources.

This business function approach allows for analysis of risks and opportunities from climate impacts across business and industry sub-sectors as well as across regions (UKCIP, 2014). Businesses first choose their site location. They then access capital and depend on employees to transform intermediate goods procured through the supply chain. These are distributed via networks as final products and services. Thus, the business function approach allows us to capture how and where goods and services are being produced, and how a company interacts with the rest of the economy. It is hoped it will assist businesses in climate risk preparedness. As a respondent to the LSE Survey (Matthews and Surminski, forthcoming) notes, “We need some joined up thinking from all sectors, with a long-term strategy...using sound and fully measured science to give informed decisions on issues”. For each of these functions we ask how this is currently impacted by climate, what impacts are expected for the future, and what responses are already being taken. Risks across functions are outlined above.



UK Climate Risk  
Independent  
Assessment (CCRA3)

# Technical Report

## Chapter 7: International Dimensions

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## Key messages

The CCRA2 Evidence Report was the first UK national risk assessment to include a chapter on the international dimensions of climate change. The evidence presented here builds on CCRA2, particularly with regard to the growing body of evidence on how direct and indirect risks can interact and amplify. This report therefore includes risks resulting directly from a changing climate (e.g., on food production, human mobility from extreme weather) as well as risks resulting from indirect effects, which are associated with conditions that weaken resilience and with risk amplification. The key messages from this analysis are:

- **Evidence since CCRA2 shows that the urgency of action for some of the risks associated with the international dimensions of climate change is greater than previously assessed. These risks include food security, violent conflict, international law and governance, and public health.** Two factors underpin this step change in assessed urgency: greater evidence of climate change acting as an amplifier of existing risk; and greater evidence of geopolitical and socio-economic background conditions that are more favourable to risk transmission and amplification. The increased urgency identified here is the result of both increased risk (e.g., UK food availability, safety, and quality) and increased evidence of risk amplification.
- **The world is more vulnerable to the transmission and amplification of risk than it was. Accordingly, this CCRA Technical Report introduces a new risk: that of risk amplification from the interactions and cascades of named risks across systems and geographies.** Risk amplification means that a risk can propagate and spill over from one sector to another, eventually cascading into a system-wide risk. Thus, even where climate is not the main driver of a global risk, its role in interacting with other factors makes it a clear contributor (see Box 7.1). The risks presented by the international dimensions of climate change are therefore systemic and are greater than the sum of the component risks identified in this chapter. Ongoing increases in hazards, exposure and vulnerability across multiple interacting risks means that there is a multiplicity of low likelihood risks and transmission pathways through which impacts can arise. The systemic nature of international risk cascades, coupled with underlying adaptation gaps resulting from lack of systemic resilience, identifies risk amplification as an area requiring additional action.
- **Changes in geopolitics have opened up new and clear cases of the need for adaptation to respond to risks to international law and governance, and to international violent conflict.** In the case of risks to the UK from international violent conflict, direct and indirect effects combine to elevate risk. Similarly, law and governance are now identified as a risk with more action needed, rather than further investigation as was the case for CCRA2. The need for action arises from an identified gap between current action and the action needed to adapt to climate change. Renewed engagement with multilateral processes and institutions would act to close this adaptation gap, since it would attenuate risk cascades by increasing cooperation and thus resilience. Whilst the short-term benefit of such adaptations is small, it rises on longer timescales, commensurate with the increase in risk magnitude. Planning is needed now in order to enable adaptation in the future.

- **International and national policy coordination is a central theme to the areas where more action is needed. Action is required to address risks to international trade routes, to UK food availability and safety, to public health, to law and governance, and from violent conflict.** The evidence suggests the risk from violent conflict can be managed through increased international coordination and active promotion of long-term political stability. This new evidence is consistent with previous evidence of the value of international coordination, for example with respect to natural disasters and food supply chains, and with law and governance, as noted directly above. The value of coordination and sharing information is also clear with regard to the international dimensions of risk to the UK finance sector. This risk emerged from the CCRA3 methodology as ‘sustain current action’ – largely because of the increase in the use of responsible investment and environmental, social, governance metrics.
- **Health risks to the UK require further action in both monitoring and raising awareness.** Whilst any single disease presents a low likelihood and high impact risk, the full set of transmission pathways across all health risks result in a medium level of risk. Adaptation actions include improved awareness of risks in both primary and secondary health care and better monitoring and surveillance of potential vectors both present overseas and in the UK. A second area of health impact presents a more direct transmission pathway: there is now some evidence of mental health issues emerging from global impacts, one of which is loss, or fear of loss, of iconic and meaningful assets or habitability of places. This limited evidence suggests that the risks to mental health associated with awareness and understanding of global impacts would be a useful topic for deeper exploration in CCRA4.
- **The evidence for action based on potential *opportunities* associated with international risk cascades has changed since CCRA2, with the result that there are now no identifiable urgent actions.** This is in part due to greater awareness of commercial opportunities, which in turn means that Government action is not required; and in part due to the known and significant uncertainties associated with these opportunities, which suggests that action is not warranted. In short, if commercial opportunities do exist, then commerce will avail itself of them. There are, however, opportunities associated with other drivers of international food systems, not least the ongoing trend towards plant-based meat substitutes and plant-based diets, which have the potential to both mitigate climate change and result in healthier diets.
- **The risks associated with human displacements have changed from more action needed in CCRA2 to watching brief in CCRA3. This is due to changes in policy rather than underlying risk.** The risks were identified in CCRA2 as requiring a more proactive strategy, to build long-term resilience in exposed regions and avoid the need to divert funds to provide humanitarian (i.e., emergency) aid. The case for action is equally clear now and is strengthened by both: i. research that has produced a better understanding of the role of policy in ensuring that climate migration produces positive development outcomes; and ii. The potential opportunities for the UK to make faster and more direct policy interventions, arising from EU exit and the creation of the Foreign Commonwealth & Development Office. Whilst the underlying evidence suggests that all other things being equal, there is still action

required on human displacement, the diversion of funds away from humanitarian aid is an active part of current policy and thus could not be deemed to be a risk.

Table 7.1 summarises the urgency scores for all risks and opportunities to the UK arising from the impacts of climate change elsewhere in the world, including the areas for further investigation, sustaining current action, and watching brief that are not covered above. International risks and opportunities are assessed for the UK as a whole, not separately for each UK nation.

<b>Table 7.1</b> Urgency scores for risks and opportunities to the UK from climate change impact overseas		
<b>Risk number</b>	<b>Risk/Opportunity description</b>	<b>Urgency Score</b>
ID1	Risks to UK food availability, safety, and quality from climate change impacts overseas	More action needed (Medium confidence)
ID2	Opportunities for UK food availability and exports from climate change impacts overseas	Watching brief (Medium confidence)
ID3	Risks and opportunities to the UK from climate-related international human mobility	Watching brief (medium confidence)
ID4	Risks to the UK from international violent conflict resulting from climate change impacts overseas	More action needed (Medium Confidence)
ID5	Risks to international law and governance from climate change that will impact the UK	More action needed (Medium confidence)
ID6	Opportunities from climate change (including Arctic sea ice melt) for international trade routes	Watching brief (Medium confidence)
ID7	Risks associated with international trade routes	More action needed (low confidence)
ID8	Risk to the UK finance sector from climate change impact overseas	Sustain current action (Low confidence)
ID9	Risk to UK public health from climate change impact overseas	More action needed (Medium confidence)
ID10	Systemic risk arising from the amplification of named risks cascading across sectors and borders	More action needed (Medium confidence)

## 7.1 Introduction

### 7.1.1 Scope of chapter

This chapter updates the second CCRA analysis of risks and opportunities for the UK from the observed and projected impacts of global climate change (Challinor *et al.*, 2016). The chapter covers a broad range of initial climate drivers and impacts including food production, violent conflict, human mobility, health and governance. Risks not only result directly from climate impact drivers (i.e., climate hazards), but also indirectly, with climate change amplifying an existing risk through perturbation of the system (see Figure 1, Challinor *et al.*, 2018). Indirect mechanisms can result from a wide range of hazards. Risks can interact geographically e.g., across borders, and through teleconnection e.g., financial, IT, wellbeing. The international dimensions of UK climate risks need to consider interactions across geographies, sectors, and transmission pathways. The growing recognition of the significance of interconnected and systemic risk, as exemplified by COVID-19, has prompted the addition to CCRA3 of Risk ID10 ‘Systemic risk arising from the amplification of named risks cascading across sectors and borders’, which takes a systems approach to understanding global risks to the UK that may have a systemic scale.

This chapter covers the risks that climate change impacts overseas present for the UK and UK interests. Many of these impacts are transmitted through the flow of goods, finance, people and information. Whilst ultimate control of such flows is typically reserved to the UK government (e.g., trade agreements, tariffs, and border controls), the risks described below have impacts across the UK. England and the Devolved Administrations (and regions within each area) may have separate governance arrangements that govern how the international risks play out in different places. For example, although the UK National Adaptation Programme (mainly covering England) is required to also cover reserved (UK-wide) policies such as defence; Scotland’s 2nd Climate Change Adaptation Programme (SCCAP2) pays attention to ensuring resilience in food (Sub-Outcome 7.1), economy (7.3) and the risks arising from climate change induced changes in international governance (7.2). Thus, whilst the UK Government may have reserved responsibility for the UK’s envelope of international risk, each devolved administration has an interest in how that risk may be transmitted within their areas.

In particular, the 2020 EU-UK Trade and Cooperation Agreement and the Internal Markets Act means that there are new challenges at the UK-EU border including from the EU to Northern Ireland. There are also new challenges to the way trade in food and goods flows around the UK differs regionally, particularly between Great Britain and Northern Ireland. This means a future shock to overseas supply chains may impact differently to the UK and across the UK from past shocks.

Many examples exist of the growing interconnectedness between countries in the production and trade of food and fibre and other socio-economic activities and their implications for generating systemic scale impacts, such as the financial crisis during and after 2008. Climate hazards play an important role in contributing directly or indirectly to this type of risk. For example, during the period 1961-2013, over half of all shocks to crop production systems were a result of extreme weather events (Cottrell *et al.*, 2019). The impacts of such climate events extend far beyond the food

system. Hedlund *et al.* (2018) derive a transboundary climate risk index of countries' exposure to transnational climate impacts (TCI). The TCI index incorporates connections between different countries based on transnational flows and interconnections reflecting four transmission pathways (biophysical, financial, people and trade, Figure 7.1) and a measure of globalisation. In this ranking, the UK lies equal 98<sup>th</sup> out of 172 countries ordered from highest (1) to lowest (172) exposure to TCI.

The impacts of climate risks will differ between socio-economic groups since specific groups of people tend to be more vulnerable and at risk: for example, economically marginalised people are more vulnerable to price rises from disrupted trade. The level of vulnerability will depend on the dimensions of inequality which include social class, income, ethnicity, age, race, disability, and gender (Oppenheimer *et al.*, 2014). Therefore, the impacts of climate change risks on society are affected by the multidimensional vulnerability of different groups (*ibid*).

### 7.1.2 Point of departure

Risk is a function of hazard, vulnerability, and exposure. The hazards arising from climate change are, in principle, predictable for a given scenario of emissions, but often with high levels of uncertainty (particularly with regard to extreme weather and its impact on wildfires or pest and disease outbreaks). However, vulnerability and exposure are mainly functions of the social, environmental political and economic contexts that govern how institutions operate and the flow of goods, finance, information or people around the world. How vulnerability and exposure change in the future is radically uncertain (Kay and King, 2020), and thus inherently unpredictable: how will trade be governed in 2080, will the world be cooperative and stable, or fragmented and unstable, will economic growth reduce or enhance inequality? Scenarios, however, could be developed to describe plausible future trends for these two components of risk but comprehensive ones are not currently available. The impacts of changing frequency and intensity of climate-related hazards, and how they interact with societal contexts to create transboundary and systemic risks, are therefore essentially unpredictable in terms of specific events and their consequences. Risks can be increased or decreased by the geopolitical and economic context in which a hazard event occurs, and so this context is as important to consider as the hazard itself. Instead, the radical uncertainty of the future suggests the need to plan better for classes of risk (such as interruptions to food supply chains) rather than attempt to predict specific risks and their transmission pathways, into the future (Kay and King, 2020).

There have been multiple case studies of food system shocks transmitted to the UK through direct supplier shortages of specific food types and indirectly through international market trade. These case studies have illustrated where an international risk can be greatly amplified by societal responses, both in the UK (e.g., 'panic buying') and internationally (e.g., food export bans fuelling price rises on international markets). Panic buying, for example, has occurred in response to both food and non-food related shocks, for example, salad and vegetable shortages following drought and storms in Europe during 2017-2018, and stock buying of supermarket essentials, paracetamol, and toilet paper, during the global pandemic of COVID-19 in 2019-2020 (as further discussed Box 7.1 and Risks ID1 and ID10).

Changes in fundamental governance structures, notably the UK's withdrawal from the EU, since the publication of CCRA2 introduce greater uncertainty about how the UK will be impacted by international climate risks. New trade relationships potentially increase the exposure of the UK to imports from countries that face more climate variability and that have poorer environmental governance (Benton *et al.*, 2019b), increasing the potential for supply-chain fragility when hazards occur (and with knock-on consequences for environmental and social governance).

This raises a more fundamental question: what does a lack of resilience to systematic risks mean for the full set of climate change risks that cascade across sectors and borders? Modern society relies heavily on the robust functioning of systems that are intricately networked, in an explicit and/or an implicit manner. While increasing the interconnectivity between infrastructure systems can result in higher efficiency of service, it also makes the constituent systems more vulnerable to cascading interruptions to flows (of goods or services) that create a system-wide or systemic risk (Centeno *et al.*, 2015; Renn *et al.*, 2019; OECD, 2020c). Such cascades of failures have been studied generally in model networks and specifically in the context of engineered systems such as the power grid, the internet and transportation and infrastructure systems, in the context of financial institutions, and within ecological systems. However, in addition to the risk of cascading failures being present within a particular domain (e.g., the network of financial institutions), there are also risks arising because of the coupling between systems in diverse domains. Indeed, the primary thesis behind many societal collapses in the history of mankind is that of a cascade of diverse risks (Szymanski *et al.*, 2015).

The world is changing increasingly fast from many different outlooks: social, economic, technical, environmental (Steffen *et al.*, 2015). We have a globally growing population, with more mobile, more connected, more wealthy people but with greater inequality between the rich and poor, collectively demanding more resources (e.g., food, water, energy, goods). There is robust and high-confidence evidence that the impact of the human resource systems on the planet is now significant (IPCC, 2019). The planet is under pressure from demand growth and its ability to withstand the environmental footprint of demand (e.g., emissions of greenhouse gases and other pollutants, soil degradation, biodiversity loss, waste, including plastic) is finite. We are now, arguably, close to the 'planetary boundaries' (Rockström *et al.*, 2009) beyond which Earth-system processes may degrade.

At the start of the 21<sup>st</sup> century, the future looked very different from how it looked in 2019, and events in 2020/21 are changing the way the interconnected world works. In the "noughties", international rules-based cooperation had led to unprecedented stability and global integration, such that there was discussion of the potential of a post-nation state world (Sassen, 2002; Ehrkamp and Leitner, 2006). Radicalism, terrorism, the threat of terror and a growing inward-looking nationalism in some parts of the world, partly driven by a crisis of liberal democracy and the economic downturn of 2008-2009, has now arguably led us to a very different world from that at the turn of the century (Bieber, 2018). Prior to COVID-19 we had significantly diverged from the direction of travel since World War 2 and the rise of the Bretton Woods' international architecture of cooperation, which underpinned globalisation: with the undermining of the UN and WTO, trade wars, increasing competition between states rather than cooperation, and the UK's withdrawal from the EU (Welfens, 2020; Weiss, 2018). On top of this change, COVID-19 has created more rapid change to the global economy than any other events since World War 2 (International Monetary Fund, 2020), and post-COVID economic reconstruction has the potential to create more changes,

both positive and negative, alongside the UK withdrawal from the EU. Given the speed of change, the breadth and depth of change, the future is very uncertain; but what is likely is that shocks (arising directly or indirectly from climate change) will be a recurrent feature. Hence, a key part of future planning must be to ensure resilience of our systems.

Our view is that the future is increasingly TUNA: turbulent, uncertain, novel and ambiguous (Benton, 2019a). This makes it difficult to define a strategic direction of travel, as the range of plausible futures for planning is very large (for example, will globalisation or de-globalisation be the trend of the next decade?) (James, 2018; Darvas, 2020; Balsa-Barreiro *et al.*, 2020). Furthermore, the potential for disruption is high given the complexity of our global systems today, and the uncertainty of how they will develop over the next decade; however, the ability to predict specific events and plan around them, is comparatively very small.

#### **Box 7.1 New and emerging diseases; COVID-19 – an example of cascading and systemic risks**

There is good theoretical evidence (reviewed in Brooks *et al.*, 2019b, Brooks and Boeger 2019a) that the emergence of new diseases can often be made more likely by environmental change (which includes climate change as well as land use change and degradation), which together disrupt ecological communities and give pathogens new opportunities to interact with new species (Altizer *et al.*, 2013). For example, Bebbler *et al.* (2013) showed that climate-related polewards spread of pests and pathogens averaged ~3km per year providing new opportunities for host, reservoirs and pathogens to interact and diseases to erupt or emerge in new places. As with an extreme weather event, however, it is very difficult to conduct an attribution study to determine the role of climate change in any particular new disease emerging. Nonetheless, it has been observed in recent decades that emerging diseases, mainly zoonotic ones from animals, are an increasing trend (Jones *et al.*, 2008; Allen *et al.*, 2017; Brooks and Boeger, 2019a) and this is an area of targeted research at present.

The driving factors behind the emergence of COVID-19 are still being actively investigated, and it remains unclear the relative contribution of climate change, wider environmental change and increasing human-wildlife interactions. Notwithstanding the attribution of environmental factors to its emergence, the way COVID-19 has propagated and created unforeseen impacts makes it a highly relevant case study for the sorts of risks being discussed in this chapter. Since emergence in 2019, in Wuhan, China the impacts on the UK have been considerable. First, the disease arrived in the UK in many independent events as travellers arrived from multiple destinations (an estimated 1356 between Feb/Mar 2020 (Pybus *et al.*, 2020) as the disease rapidly spread round the world (Skums *et al.*, 2020). Second, lockdowns around the world created disruption to transport networks of goods (Zhu *et al.*, 2020), as planes were grounded and borders became restricted (for example, lack of aeroplanes to Kenya, impeded the import to the UK of fresh produce: even by July 2020, Kenyan exports of fresh produce remained at 25-30% of full capacity (FEWSNet, 2020)), as well as labour shortages in some industries. Most noticeable in the early stages of the pandemic were shortages of PPE – partly through changing global demand, partly because many were sourced from China (where the first major lockdown occurred). Third, lockdowns produced major changes in demand, and this demand shock led to significant impacts on the UK's supply chains (noticeably through the closure of the hospitality sector, leading to significant wastage of food – including meat, milk – that was destined for sale). Fourth, restrictions on movement, closure of hospitality and a significant increase in working from home have led to significant changes in the UK and global economies, which may take decades to recover fully from. Finally,

the pandemic has led to the potential for large scale structural change in the UK economy: changing working practices, attitudes, and need to ‘build back better’ where ‘better’ includes greater resilience (OECD, 2020b).

All in all, COVID-19 is an example of a risk cascade which spills across sectors from a health issue overseas to create society-wide or systemic risks that far exceed the impact on the health system (OECD, 2020c): the overall economic impacts to the UK (as of Sept 2020) are ~100x greater than the actual cost of healthcare (Lilly *et al.*, 2020). The emergence of a new disease has cascaded around the world – through people movements and supply-chain, disruptions - leading to an ongoing shock of enormous magnitude.

### 7.1.3 Transmission pathways and framework for international dimensions of risk

The rapidly growing interest and research on interconnected systems and systemic risk use a range of terms with similar meanings, sometimes interchangeably. Table 7.2 lists the key terms and their meaning adopted for this chapter. Conventional risks are those that are recognizable within an experienced set of circumstances (e.g., a salmonella outbreak) and are managed with standard risk-based regulation. Emerging risks are new or known but identified in a new context (e.g., a novel disease like COVID-19). Emerging risks carry more uncertainty in terms of their drivers and management and therefore require monitoring, attribution of triggers, and adaptive responses. Systemic risks occur when an impact of a threat or failure moves through a complex and interconnected system and impacts widely. For example, the impacts of a pandemic are not just on health, but also on the flow of goods, the movement of people, and the wider economy. Systemic risks display non-linear behaviour, limited attribution to any one driver, and tipping points that are likely to be unknown or highly unpredictable. Systemic risks therefore require a focus on adaptation, resilience-building, and transformation of organizations and systems (IRGC, 2018).

Besides the direct impact of a hazard, such as a flood on an affected locality, societal responses to a hazard and the threat of the hazard’s impacts, can also have significant consequences for the way the risk cascades through transmission pathways impacting on sectors and different geographies (Pidgeon *et al.*, 2003). These wider, ripple, cascading or indirect impacts can be independent of the magnitude of the direct impact of the hazard. This response or pre-emptive response – such as erecting barriers to trade to protect local markets – can act to attenuate or amplify risk and act to drive the transmission of risk across geographies or through teleconnection (Challinor *et al.*, 2018; Kaspersen *et al.*, 2003). The transfer of information and data is likely to be an increasingly prominent pathway of transmission in a more globally connected society, especially through greater connectivity by social media, real-time news reporting, and the internet of things.


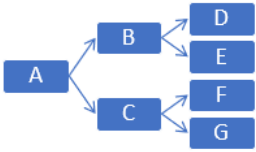
Many of the identified levers of social amplification of risk (heuristics and values, social group relations, signal value, stigma and trust) are driven through sharing of information and data (Kaspersen *et al.*, 2003). It therefore follows that it is possible for a climate hazard to stay the same, but the risk to society to increase due to changes in the way risks are transmitted or propagated through the system. As a result, some of the changes in assessment of risks from CCRA2 to CCRA3 arise not because we have fresh knowledge of climate hazards overseas, but due to structural



changes in (a) geopolitics and the multilateral architecture of international competition, (b) the UK leaving the EU and (c) structural changes in economies caused by COVID-19 and its aftermath.

The impact of structural changes in geopolitics and economics can either reduce or increase the adaptation gap (see Chapter 2: Watkiss and Betts, 2021). In the case of risks from international violent conflict resulting from climate change impact overseas (section 7.6), there is increasing evidence of both risk cascades and direct climate impacts, thus suggesting a widening adaptation gap. In the case of opportunities for UK food availability and exports from climate impacts overseas (section 7.4), the adaptation gap has narrowed. The call in CCRA2 for active monitoring, to capitalise on emergent comparative advantage, has given way to greater awareness of commercial opportunities, with a greater likelihood that the market will therefore take advantage of any opportunities directly. This awareness, coupled with the significant uncertainties associated with these opportunities, has led to this opportunity now being designated as watching brief rather than an area for further investigation.

**Table 7.2** Terminology used in this chapter. Terms used in this chapter in bold and alternative forms used in the literature, see for example IPCC (Oppenheimer *et al.*, 2014; all ‘quotes’ are from pages 1048-49); IRGC, 2018; Benzie *et al.*, 2016; Nyström *et al.*, 2019; UNISDR, 2009. These descriptions are consistent with the CCRA3 glossary but are nuanced in order to deal with the systemic nature of the risks covered in this chapter.

Term (+ alternatives)	Description
<b>Systemic risk</b> (similar terms include hyper-risks, Anthropocene Risk)	Risk which propagates through a complex and interconnected system, creating a risk cascade that has system-wide consequences. For example, where a climate hazard interrupts supply chains, leading to economy-wide impacts.
<b>Transmission pathway</b> (Risk Chain)	Linear transmission of risk, from primary to secondary to tertiary impacts 
<b>Risk Cascade</b> (similar terms includes spillover, and cascading)	The non-linear transmission of risk across multiple impacts. Sufficiently large cascades can create systemic impacts (see systemic risk). 
<b>Geographical Risk</b>	Risk transmitted across a border or geographical boundary.

<b>Teleconnection Risk / Connected risk</b>	Risk transmitted through non-geographical links, for example, via trade flows.
<b>Conventional risk</b>	Risk recognizable and stable in a set of circumstances and managed with standard risk-based regulation.
<b>Emerging risk</b>	‘A [novel] risk that arises from the interaction of phenomena in a complex system’.
<b>Risk amplification / attenuation</b>	The increase / decrease of the risk and its impact due to broader conditions, e.g., political, social and economic drivers. This amplification / attenuation of risk is different from just the sum of risks.
<b>Social amplification / attenuation</b>	Risk amplified / attenuated by a societal response (including policy/political response).
<b>Direct (first order) effects</b>	Direct impact caused by climate hazard (e.g., storm damage).
<b>Indirect effects (second, third order etc.)</b>	Indirect (or 2 <sup>nd</sup> order) impacts occur as a result of a transmission pathway across space (e.g., damage interrupts supply chain leading to “teleconnection” between geographies) and/or aspects of society and environment (e.g., damage affects livelihoods leading to subsequent abandonment of land and change in local economy).
<b>Multidimensional Vulnerability</b>	Systemic vulnerability arising from concatenation of circumstances (e.g., food price shock arising from climate hazard on top of fuel price rises, low stocks and low transparency in supply chains). This includes intersecting dimensions of inequality, including gender, wealth, social class, ethnicity, age, race and disability.
<b>Systemic risk (amplification / attenuation)</b>	Systemic risks occur when the outcomes of a hazard propagate widely across space or sectors to create system-wide impacts on economies or societies. The risk can be amplified or attenuated by interactions across disparate parts of the system.

In the CCRA2 Evidence Report (Challinor *et al.*, 2016), Chapter 7, the interactions between global climate and the UK are categorised as:

- interactions between markets and economic interests.
- the flow of goods, services, and people between the UK and the rest of the world, and
- the placement of the UK within the EU and international political system, including its responsibilities and cultural ties to other parts of the world.

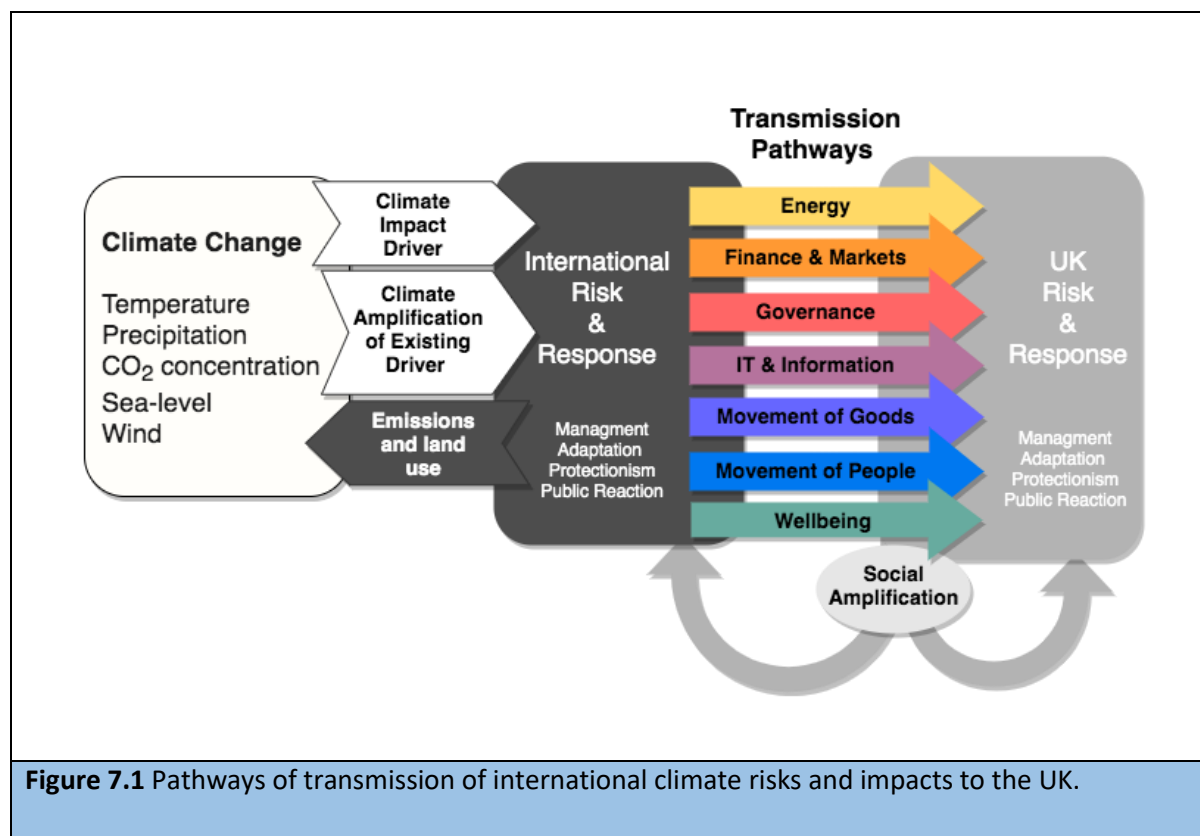
Complementary literature has established the importance of identifying the pathways that enable risk transmission and different authors propose alternative combinations but with many elements in common. For example, Moser and Hart (2015) identified the following pathways: “(1) trade and economic exchange, (2) insurance and reinsurance, (3) energy systems, (4) food systems; (5) human

health, (6) population migration, (7) communication, and (8) strategic alliances and military interactions". Benzie *et al.* (2016) identify four climate risk pathways through which climate impacts can transfer, namely people, trade, finance, and biophysical ways, and consider infrastructure to be a transmission pathway.

Drawing insights from the second UK CCRA, Challinor *et al.* (2018) identify significant challenges to the incorporation of climate and resource-generated systemic risk through multiple risk transmission mechanisms into national climate assessments. They (*ibid*) stress that climate risk assessments (and therefore also national adaptation programmes) that only consider a single region or jurisdiction will fail to capture the complex mechanisms and interdependencies that transmit and amplify risk. While examples of approaches that consider these issues are emerging, they remain stand-alone and ad hoc with respect to climate drivers, sectors, locations and time periods such that beyond CCRA2 at present there are no systematic assessments of these types of climate-induced risks and the adaptation response in relation to the UK.

Here, we present and use a framework that includes the most common transmission pathways through which risks occurring outside the UK may cascade into the UK drawing from various sources (Challinor *et al.*, 2016; IRGC, 2018; Benzie *et al.*, 2016; Moser and Hart, 2015; Challinor *et al.*, 2018, King *et al.*, 2015). The framework (Figure 7.1) identifies seven common transmission pathways: energy, finance and markets, governance, IT and information, movement of goods, movement of people, and wellbeing. These transmission pathways allocate resources and transmit risk to and from the UK (see e.g., the review of Challinor *et al.*, 2018). The far left of the figure shows that feedbacks from the UK response to risk can transmit and amplify risks internationally. This recognises that there is potential for amplification when multiple risks are transmitted through the same pathway (convergence) – such as food prices being affected by simultaneous shocks from different events - and when risks transmit through multiple pathways into the UK at the same time (co-occurrence). The framework provides a consistent basis for reviewing the key risks identified by CCRA, following the established approach (See Chapter 2: Watkiss and Betts, 2021). The framework includes more transmission pathways than CCRA2, but the analytical approach is very similar because in most examples there is insufficient evidence to consider all transmission pathways systematically.

For any given climate hazard, there is a very large number of factors that can lead to risk amplification (and cascades across sectors and borders) or risk attenuation, depending on the extensive range of political, social, and economic drivers. For example, the same event occurring during COVID-19 lockdown, and in a normal year, may have radically different consequences for market dynamics. Furthermore, with risks transmitting across space, the perception of a near-term *future* impact can cause the social amplification of risk that can be as important as the impact itself, depending on whether there is already sentiment that a system is under pressure. Thus, a given climate hazard has very contingent outcomes on risks, which makes standard climatic risk assessment methods impossible to implement. While there is a range of methods that can be applied (see e.g., Challinor *et al.*, 2018), it is not possible to assess how risks vary quantitatively according to each emission scenario.



This chapter refrains from listing key climate indices or identifying specific climate impact drivers, since cascading international climate risks are mediated through indirect effects, which contrast to the direct effects driving the climate impacts assessed in previous chapters. A given risk outcome in the UK, for example, a price spike and reduced supermarket food availability, could occur in response to a vast range of climate drivers across a global setting: a drought impacting on agriculture, novel pests and diseases responding to climate events, extreme weather impacting on transport logistics (heat buckling key rail routes, hurricanes affecting ports; drought affecting Mississippi river transport; storm surge affecting channel ports in the UK; wildfires disrupting transport or logistics); emerging diseases affecting humans and labour in the food system; climate migration causing slower flows at borders, disrupting just-in-time supply chains etc. The complexity of causal pathways and the linkage between changing hazards due to climate change and global supply chains means there is very little direct mapping between a climate driver and a risk outcome.

#### 7.1.4 Socio-economic change

Social and economic trends are highly relevant to the future risks of climate change, and strongly influence future magnitude through changes in exposure and vulnerability (Chapter 2: Watkiss and Betts, 2021). Climate and socio-economic factors can act together as risk multipliers, although for some cases, socio-economic change can reduce vulnerability and thus dampen impacts.

For CCRA3, the CCC commissioned a new consistent set of UK socioeconomic projection data from Cambridge Econometrics (CE) (2019) as one of the research projects. Whilst this research only considered UK projections (e.g., for population, economic growth), it is clear that these sorts of changes in the UK will influence international risks, as will parallel changes outside the UK.

In the context of this chapter, and the international risk cascades set out above in Figure 7.1, there will be a major influence from future global socio-economic drivers, many of which are unknowable over the course of the century (for example, the future of international cooperation, international governance, the future of capitalism, democracy, and inequality). This adds another dimension of complexity to the consideration of international risks, through the amplification or attenuation (dampening) of international risk and transmission pathways. There are global socio-economic projections available in the IPCC Shared Socio-economic Pathways (SSPs) (O'Neill *et al.*, 2014), outlined in Chapter 2 (Watkins and Betts, 2021), which span the dimensions of challenges to mitigation and adaptation, though they are insufficiently comprehensive to guide an analysis of risk transmission across economies globally embedded. The SSPs provide “high-level” alternative futures which encompass some of the trends highlighted above. It is notable that when the SSPs were selected, there had been a long period of stability and it was difficult to foresee the future in terms other than a SSP2 – ‘Middle of the Road’ scenario. As the discussion above has highlighted, much has changed since then and considerations of alternative futures (e.g., of greater Regional Rivalry) no longer look so unlikely. While some data exist for the SSPs (e.g., quantitative data on population and economic growth, at the country level) it is extremely difficult to use these to try and assess the implications for the international risks set out in this chapter, at least in a synthesis such as the CCRA3 Technical Report. For this reason, these socio-economic scenarios are not included here, though we highlight that various futures could increase the likelihood of particular risks. Further work is being done through the current UKRI Strategic Priorities Fund Climate Resilience programme to expand the socioeconomic data for the UK into a set of scenarios that can be used for CCRA4.

Finally, since CCRA2, the UK, Scottish and Welsh Governments have adopted net zero emissions targets into law. This has important implications for the UK domestically, including for future socioeconomic trends, but it is stressed that the net zero target does not apply to emissions generated outside the UK which will largely dictate UK climate change impacts.

## 7.2 Risks to UK food availability, safety, and quality from climate change impacts overseas (ID1)

Climate change exacerbates disruptive events impacting on agricultural production and food supply chains (droughts, agricultural pests and diseases, storms), with increased risks of disruptions associated with multiple production areas (e.g., simultaneous impacts in the USA and Europe); climate change will increase the likelihood of risk cascades amplifying the impacts (Challinor *et al.*, 2016; IPCC, 2019; Kornhuber *et al.*, 2020; Gaupp, 2020; Gaupp *et al.*, 2020; Mann *et al.*, 2017). Increasing risks implies a requirement to develop food systems that are resilient to disruption, rather than focussing on supply chain efficiency, which increases fragility (Benton, 2020b; Liu *et al.*, 2020). Climate change affects the yields of crops, livestock, aquaculture and wild-caught fisheries (IPCC, 2019; Gephart and Pace, 2015; Lam *et al.*, 2016; Froehlich *et al.*, 2018; Free *et al.*, 2019). There are multiple lines of evidence indicating overall global yield decreases in response to rising temperatures and increasing water scarcity (Long *et al.*, 2006; Schleussner *et al.*, 2018). These include evidence attributing *observed* yield decreases to climate change (Porter *et al.*, 2014, Ray *et al.*, 2019 and Wake, 2019). Thus, there is robust evidence with high confidence (e.g., IPCC, 2014; Porter *et al.*,

2014) that globally yields will continue to decrease with increasing global mean temperature. Porter *et al.*, (2014) reviewed the literature for instances of yield increases and decreases from modelling projections, showing clearly a shift from an approximate 50/50 split between the two categories in the near term moving to less than 25% of simulations showing yield increases by the end of the century. This result, and numerous specific studies, suggest that agro-climatic thresholds at the local and regional level contribute to gradual yield decreases over time or with an increasing magnitude of climate change.

The biggest risks to food security in the UK, however, are not the long-term changes in the average yields, but the variability in access to food (and its ingredients) associated with supply-side disruptions arising from variability in the weather, and the potential for cascading and interacting risks. This was explored in depth in the CCRA2 Evidence Report Chapter 7 and IPCC SRCCL (IPCC, 2019): for example, the food price spikes in 2007/8 and 2010/11 arose from climate-related disruptions to production, interacting with a range of other factors *inter alia* lack of transparency in holdings, biofuel policy incentivising the use of grain for fuel, and poor policy decisions that created price amplification and lack of economic accessibility around the world (CCRA2 Evidence Report; Bailey *et al.*, 2015).

A very wide range of climate hazards can cause impacts through the markets, especially extreme weather events in key production areas (termed breadbasket regions) (Betts *et al.*, 2018; Kent *et al.*, 2017; Mann *et al.*, 2017). An increasing risk of teleconnection between areas can also lead to multiple areas suffering impacts simultaneously (e.g., through jet stream effects) (Betts *et al.*, 2018; Kent *et al.*, 2017; Mann *et al.*, 2017). In addition, impacts can arise from climate-related outbreaks of pests and diseases that may affect global production and market prices (e.g., locust swarms affecting the Horn of Africa in 2020 (Salih *et al.*, 2020)<sup>1</sup>), or outbreaks of human diseases that may emerge from climate change's disruptive impact on ecology (see Box 1 and ID9) or are exacerbated by climate change in their impact (for example, COVID-19's impacts are weather-influenced, e.g., Tosepu *et al.*, 2020). Finally, climate change can impact the supply of labour through increased exposure of the agricultural or supply-chain workforce to, for example, heat stress (Simpson *et al.*, 2021). Furthermore, as explored in detail in ID7 (below), weather can cause trade interruptions via its impacts on ports. All these overseas impacts on production and transport can affect food prices and markets in the UK due to market connections. As extreme weather (see Chapter 1: Slingo, 2021 and IPCC, 2019) is increasingly prevalent (high confidence, robust evidence), the potential for increased disruptions in supply chains is likely.

The situation for marine production is broadly similar to that of food crops. The body size (meat yield) of several globally important fish species is likely to decline with projected changes in the ocean with future projected climate change, for example a mean decrease in landed catch (26 % yield decrease per recruit) recorded for 6 of the 8-commercial fish in the North Sea, attributed to a 1–2-degree temperature increase over a 40-year period (Bauldron *et al.*, 2014). Reduced oxygen

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<sup>1</sup> The 2020 locust swarms, despite affecting areas without significant exports, none the less are likely to have impacts on global grain prices (see <https://agfax.com/2020/06/19/grain-markets-africa-asian-locusts-will-have-major-impact-on-global-production-dtn/>).

content, associated with warming oceans, is also expected to further decrease fish body size with climate change (Deutsch *et al.*, 2015).

In a modelled global impact assessment with projections of global warming reaching 3.2°C to 5.4°C at the end of the century<sup>2</sup>, fin-fish production in aquaculture is projected to decline by 10-20% in Indo-Pacific, Mexico and Canada by 2050-2070, and less substantial declines in Norway and China by the end of the century. Potential for increase in production is projected for the Caribbean and Mediterranean. Bivalve production is projected to have a more severe decrease, in the range of 50-100% in China, Thailand and Canada (Froehlich *et al.*, 2018). Toxic algal blooms (linked to global asthma prevalence in Walsh *et al.*, 2017), anoxia and disease outbreaks are further threats to marine production and human health, that are likely to shift production area and trade flows, but despite being linked spatio-temporally to climate (e.g., Leung *et al.*, 2013) these drivers remain challenging to project under future climate change (Froehlich *et al.*, 2018).

It is only in recent years that impacts on food safety and quality have been assessed (see IPCC, 2019 for a recent overview). Climate change can, for example, affect the occurrence of mycotoxin-producing fungi, or of micro-organisms in aquatic food chains that cause disease (e.g., dinoflagellates, bacteria like *Vibrio*, associated with warm-water upwellings) (Martinez-Urtaza, 2010). It is also suggested that climate change could increase the risk of flood-related contamination of pastures with enteric microbes (like *Salmonella*) that can enter the human food chain (Jiang *et al.*, 2015). Degradation and spoilage of products in storage and transport can also be affected by changing humidity and temperature outside of cold-chains, notably from microbial decay but also potential changes in the population dynamics of stored product pests (e.g., mites, beetles, moths) (Moses *et al.*, 2015). The projected impact of increased aflatoxin contamination under future climate scenarios has been evidenced and estimated empirically in global climate modelling studies (Battilani *et al.*, 2016) assessing the impact on human ingestion, which in turn has been associated with human health outcomes including cancers, immunotoxicity, renal diseases, and gastroenteritis (Wu *et al.*, 2014).

Climate change may affect the quality of food in other ways: changing heat stress in poultry, as well as affecting yields, can affect meat quality by both altering fat deposition and meat chemical constituents (Lara and Rostagno, 2013). In addition, CO<sub>2</sub> fertilisation, which might improve crop yields (see section 7.4) can be detrimental for micro- and macro-nutrient quality: Zhu *et al.* (2018) report a meta-analysis of FACE trials on a range of rice cultivars. Protein declines by an average of 10% under elevated CO<sub>2</sub>, iron and zinc decline by 8% and 5% respectively. Furthermore, a range of vitamins show large declines across all rice cultivars, including B1 (-17%), B2 (-17%), B5 (-13%), and B9 (-30%), whereas Vitamin E increased.

Projections of changes in nutritional content of food production associated with increasing levels of CO<sub>2</sub> suggest significant negative impacts. Smith and Myers (2018b) assess global impacts on health from the projected decrease in nutritional content of food in response to 550ppm CO<sub>2</sub>. These were estimated as: an additional 175 million cases of zinc deficiency, and 122 million protein deficient. For

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<sup>2</sup> An ensemble of CMIP5 models with the RCP8.5 concentrations pathway. In the ensemble used in IPCC AR5 the 5<sup>th</sup> to 95<sup>th</sup> percentile range of warming reaches 3.2°C to 5.4°C in 2081-2100 (see Chapter 1: Slingo, 2021)

iron, additional cases could not be calculated, but high-risk regions were identified: where over 20% of the population are currently anaemic, and the average iron consumption is estimated to decrease by 4% or more. Smith and Myers did not attempt to quantify the health burden of worsening deficiencies and health outcomes, which remains un-estimated, but is expected to be large, here only the additionality of case numbers is reported. High risk areas were identified as 'South and East Asia, North Africa, the Middle East, eastern and southern Africa, and Southeast Asia'.

## 7.2.1 Current and future level of risk (ID1)

### 7.2.1.1 Current Risk (ID1)

The CCRA2 Evidence Report Chapter 7 found that the absolute availability of food is not likely to be an issue for the UK as a whole as a consequence of climate change up to 2100 (Challinor *et al.*, 2016). However, as the international food system becomes more exposed to climate-related hazards, food price spikes may become increasingly likely. This, in turn, changes the accessibility to food, particularly for the economically marginalised. Evidence since CCRA2 shows that the frequency of extreme weather events (including the conditions that lead to wildfires) is increasing, with some suggestion that these increases exceed what climate models predicted (Sarhadi *et al.*, 2017; Balaguru *et al.*, 2018; Li *et al.*, 2018). Previously low-probability events have become more common, most noticeably in 2019 extreme heat events and tropical storms (National Academies of Sciences, Engineering, and Medicine, 2016). There is also evidence that specific patterns of jet streams pose a significant threat to food production through multiple simultaneous harvest failures globally (Kornhuber *et al.*, 2020). Climate change, through increasing extreme events, therefore, advances its potential for direct and indirect effects on food supply chains.

The literature on market interactions from 2015-2019 has also been consistent with the message of the second CCRA Evidence Report, illustrating how global trade has the potential to exacerbate risk, under certain circumstances, and that market mechanisms alone are not fully able to counter the volatility of prices and production (and distribution) due to the climate's impact on food production (Challinor *et al.*, 2016). If shocks are sufficiently large, market amplification can occur that requires public policy solutions.

The principal risk interactions and amplification evidenced are feedbacks between climate-induced food shortages (including reductions in quality and safety), and market behaviour, which includes levels of stockholdings (Marchand *et al.*, 2016; Heslin *et al.*, 2020), and associated transparency. These risks to the UK may result from multiple transmission pathways such as finance & markets, and the movement of goods. Reactionary protective policy (such as export bans) can also be a key factor in amplifying effects, especially where the UK depends heavily on particular regions abroad for a specific import or export product (Dithmer and Abdulai, 2017; Brown *et al.*, 2017). These risk interactions apply across crops, livestock, aquaculture, and wild-caught fisheries (Gephart and Pace, 2015; Lam *et al.*, 2016; Froehlich *et al.*, 2018; Free *et al.*, 2019). Volatility in food supplies and prices also increases risks arising from food fraud, as there is then greater incentive to substitute expensive and less available ingredients for cheaper ones (Challinor *et al.*, 2016).



The amplification of impacts from concurrent climate-induced agricultural shocks via global trade was assessed in a single scenario modelling activity by Lunt *et al.* (2016) and Lloyds (2015): the scenario investigated the cascading financial impact due to the co-occurrence of staple food production failures (a decrease of 10% maize, 11% soy, 7% wheat and 7% rice, which currently individually each have roughly a 1-in-200 return probability). This scenario led to simulated food price rises of 500%, and public agricultural commodity stocks increase in share value by 100%. Food price rises led to food riots in the Middle East, North Africa, and Latin America, and the cumulative loss of 5-10% on European and US stock markets (Lunt *et al.*, 2016, Lloyds, 2015). This amplification of the impact of climate extremes through systemic risk in complex food systems can be a bigger contribution to loss than direct loss caused by the event (Acemoglu *et al.*, 2012) (see also discussion in ID10 below).

Current risks to food safety were also reviewed in CCRA2, where it was concluded that, despite clear climate-induced food safety issues overseas, there was little evidence of unsafe food entering the UK. There is, however, evidence of risk to food quality in the UK resulting from climate change impact overseas. For example, Hurricane Florence in the USA in 2018 significantly affected the production of sweet potato (The Grocer, 2018). A diversification of import regions to include Egypt and Central America resulting in a decline in the quality of sweet potato available in the UK has been reported as a result (Fresh Plaza, 2018).

#### 7.2.1.2 Future Risk (ID1)

The introductory section above highlights the ways that food supply and agricultural production have been, could be, and are projected to be impacted by climate change. Furthermore, as outlined in the introductory section, future risks depend on hazards, vulnerability, and exposure. The former is uncertain (but climate hazards are in principle predictable), the latter two are radically uncertain (Kay and King, 2020), depending on geopolitical, economic, institutional, and social factors (e.g., international cooperation and governance, inequality, border controls). Given the last decade's drivers away from the international architecture of multilateral cooperation and increasing geopolitical uncertainty, at the moment, all components of the risk equation (hazards, exposure, and vulnerability) seem to be increasing the overall risk of disruptions. This may be countered by an increased focus on resilience-building, but the current assessment is that future risks are more likely to increase.

#### **Box 7.2** Case Study: Fresh produce shortages in 2017

At the time of the second CCRA (2014-2017), there was no evidence of climate shocks producing food shortages in the UK. However, an area of concern is the extent to which the UK relies on fruit and vegetable imports, over 80% of fruit and about 50% of vegetables consumed are imported. At certain points of the year this flow is particularly key. The vegetable shortages of early 2017,

which came as the UK government published its response<sup>3</sup> to the evidence report for CCRA 2017 (citing a ‘more optimistic view ... of markets’), were the result of climatic shocks to the food system.

Poor growing conditions in key sourcing regions, such as Murcia in southern Spain, resulted in rationing and price increases of up to 25-300% across the UK. Shortages were mostly encountered in lettuce, but also courgette, aubergines, tomatoes, peppers, broccoli, cauliflower, onions, carrots and celery. Multiple drivers of shortages were identified, including flooding in South East Spain, and cold temperatures in Italy (BBC News, 2017a, b; Guardian, 2018). In Spain, the highest rainfall in 30 years reduced the area of arable land to only 30% of the area planted (BBC News, 2017a). Italy shifted from exporting over European winter to importing (BBC News, 2017a). Traders imported from the US to fill the shortfall, thus increasing cost, emissions and contaminants associated with the produce. (BBC News, 2017a).

During the vegetable shortages of 2017, some catering and restaurants were bulk buying from supermarkets instead of wholesale at this time, in response to the shortages and price spikes. Some supermarkets appeared to opt for empty shelves rather than paying the higher price. Shortages appeared to be supermarket dependent, with, for example, the Co-op not reporting shortages (BBC News, 2017a). This suggests that vulnerability may be the result of a high proportion of imports coming from one region (BBC News, 2017a). It also suggests that supply chain management might reduce the future impact of events of this kind. Indeed, some companies have since diversified their growers’ networks. For example, Florette have mitigated future risk due to production shortage in Southern Spain by moving the grower network of some supply to Northern Spain, Southern France and Northern Africa (inews, 2018). Nonetheless, events of this sort continue to occur, and interact with UK growing conditions to produce shortages, as in the case of cauliflower in August 2019 (Guardian, 2019; BBC News, 2019).

As highlighted in CCRA2 Chapter 7 (Challinor *et al.*, 2016), the socioeconomic and demographic inequalities across the UK result in different exposures and vulnerabilities to the risk of food price spikes. More broadly, environmental hazards exist everywhere and can be related to income, education, employment, age, sex, race/ethnicity and specific locations or settings. In addition to these differences in exposure, inequalities are also caused by social or demographic differences in vulnerability towards certain risks. For example, supermarket shoppers in cities may be exposed to variations in food prices or supply, and they will be differentially vulnerable to price rises, according to their income. Shoppers in rural locations, with access to smaller and more highly dispersed retail outlets, will be exposed to different risks as availability of food will vary more, as well as its price.

EU-Exit is also a complicating factor affecting these risks for at least two reasons. First, it will change existing patterns of trade, one major risk transmission pathway; any disruption to just-in-time supply

3

[https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/584281/uk-climate-change-risk-assess-2017.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/584281/uk-climate-change-risk-assess-2017.pdf)

chains causes impact because there is no internal capacity to buffer disruption: especially for fruit and vegetables at some times of the year, the speed which they enter the country is the speed at which they are sold. EU-Exit risks disrupting trade through new border arrangements, as well as through moving from existing trading partners to new ones. During this process, which may take years during which the UK develops new trading relationships, the UK is likely to be more vulnerable to supply chain disruptions. Food price spikes caused by climate events elsewhere, such as the 2007/8 and 2010/11 Australian and Russian heatwaves, if they happened now would potentially be amplified by new border processes or friction caused by new trading relationships or unfamiliar regulatory standards from new partners.

The second key EU-Exit factor is that prior to leaving the EU, much of the UK's food trade was with European countries with similarly high standards of environmental governance. Relying increasingly on new and emerging markets has the potential to expose the UK to increased climatic risks as many potential new partners are exposed to higher climate-related risks, or lower ability to govern them (e.g., citrus may come from Morocco rather than the EU) and also to poorer governance of natural resources (water, emissions, biodiversity). The countries which have been traditional major trading partners for the UK typically have significantly higher environmental and social governance than countries we may seek to increase future food trade (Benton *et al.*, 2019). Both increased border friction and new trading partners may decrease the long-term resilience of supply chains.

Food trade is a reserved issue to the UK Government, but local and regional food security depends on intra-UK food supplies (a significant part of which is imported). The relationship between the internal and external markets depends on new legal frameworks embodied within the 2020 Internal Markets Act. Local governance of food issues, particularly food safety, is also devolved, as is agricultural policy. This means there is potential for an external food trade 'shock' to resolve differently across the DAs – with different implications for food prices and availability in the different regions of the UK.

In particular, there are currently increased challenges for trade between Great Britain and Northern Ireland, although NI is more aligned with Ireland and the EU (Birnie and Brownlow, 2021). In recent times, significant trade from Ireland to the rest of the EU has crossed through GB, with implications for the transmission of risks from the UK to the island of Ireland with interruption affecting major supply routes into the UK (especially the Channel and East Coast ports). In the future, there may be the growth of more direct sea crossings from Eire to the EU. Hence, there is potential for NI to be supplied via trade that comes both from (or via) GB and directly from the Continent. Depending on how any risk may eventuate this may increase the resilience of NI's supplies.

#### 7.2.1.3 Lock-in and thresholds (ID1)

The food system is an example of a complex system, which tends towards internal stability and resistance to change which creates inherent lock-ins that limit flexibility and adaptability (Oliver *et al.*, 2018). This has been indicated by COVID-19, where just-in-time supply chain fragility was highlighted, and closure of the hospitality sector led to increased waste as supply chains could not adapt to supplying the retail sector. Lack of consideration of potential environmental governance

and exposure to climate risks in post-EU-Exit development of free trade agreements could also undermine the ability to have a resilient food system as climate risks mount.

Clearly, there is potential for thresholds in global climate dynamics, caused by passing climate tipping points (e.g., permanent changes in the jetstream or overturning circulation) that could have major implications for the global food supply (Benton, 2020a). The potential for these – and the timescale over which they may impact – is currently unresolved.

#### 7.2.1.4 Cross-cutting risks and Inter-dependencies (ID1)

The nature of risks cascading across space, sectors and geographies is one of inter-dependence. Food supply relies on land, water, labour, finance, inputs (to agriculture and food production and packaging), transport logistics, multiple families of policy and so on. As detailed in CCRA2 (2017), the climate hazard – whether on production or supply chains – can spark market and political responses that may further be exacerbated by other factors (such as other policies: biofuel policy in 2007/8; or other conditions – low transparency of stockholdings).

Despite progress since CCRA2, it remains very difficult to make quantified risk statements that draw links between international climate events (specific climate indices and their future projected ranges) with risk outcomes in the UK. The distal nature of the risk, both in terms of complexity, number of risk interactions, risk amplification and geographical proximity implies serious limits to predictability (see e.g., Morris *et al.*, 2017) (see ID10 below). Nonetheless, observed links between climate shocks abroad and food price spikes in the UK are well documented (e.g., Challinor *et al.*, 2016; Challinor *et al.*, 2018).

#### 7.2.1.5 Implications for Net Zero (ID1)

Net-zero commitments globally clearly have the potential for interacting with food supply issues in two ways. First, countries may incentivise land-based carbon dioxide removal that may act to increase land competition for agricultural production (IPCC, 2019). This may tighten supply relative to demand and therefore increase systemic pressure (Challinor *et al.*, 2016; Challinor *et al.*, 2018). Particularly if weather impacts further tighten supplies in a given harvest year, this tightening of supply can act to amplify price signals towards a price spike. Second, countries – including the UK – may act to incentivise dietary change to reduce land- and carbon-footprints from food, for example by encouraging a shift towards plant-based diets that may also be healthier. Such moves on the “demand side” may disincentivise producers (e.g., of animal-sourced foods), and impact the availability of the affected foods, and therefore their price.

#### 7.2.1.6 Inequalities (ID1)

The impacts of food price spikes, safety, and quality issues are differentiated across society, with those on lower household incomes less buffered than higher earners. COVID-19 has highlighted the extent to which significant proportions of the UK population are ‘just about managing’ in normal circumstances. The Food Standards Agency in 2019 (Fuller *et al.*, 2019) estimated that, in the course of a year, about 10m UK adults had, at some time, experienced an inability to feed themselves.

However, this part of the population struggles to meet basic food needs in extremis. A report from The Food Foundation found that in the first two months of lockdown in Spring 2020, adult food insecurity increased four times. This arose from (a) reduced income and squeezed budgets, (b) lack of stocks in supermarkets to meet increased demand (particularly in the first weeks of lockdown), (c) lack of ability to access shops (due to disability, child-care, or quarantine) (Loopstra, 2020).

Decreasing food nutritional content from increasing CO<sub>2</sub>, or impacts particularly on more fragile, more just-in-time fresh produce supply chains may both decrease the nutritional density of fruit and vegetables and reduce its availability, stability, and accessibility: making it more difficult and more expensive to eat healthily. This has the potential to interact with existing trends of increasing obesity, and hidden hunger, (both of which are related to inequality in incomes) in the UK and internationally. Populations at the highest risk are concurrent with those at risk of obesity and malnutrition (Drewnowski, 2012; Jones *et al.*, 2014b). Therefore, addressing food access inequality, access to fresh produce, and informed dietary choices, will likely have the co-benefit of reducing vulnerability to the risk of decreasing nutritional quality of food produced due to climate change (IPCC, 2019).

#### 7.2.1.7 Magnitude Scores (ID1)

<b>Table 7.3</b> Magnitude scores for the risk to UK food availability, safety, and quality from climate change impact overseas					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>UK</b>	High  (Medium confidence)	Medium to High  (Medium confidence)	High  (Medium confidence)	Medium to High  (Medium confidence)	High  (Medium confidence)

Given the evidence of today's risks (significant disruptions to yields and supply chains caused by climate hazards, and climate-related ecological hazards, such as emerging pests and diseases in the past decade), the evidence suggests the magnitude of the impact is high, though the probability of the risk occurring may be lower. This is based on the potential for a significant proportion of the UK's population to be affected by a food price spike, as per 2007/8 and 2010/11, as well as the impacts of COVID-19 on food insecurity in the UK. Looking ahead, the known increase in the underlying climate hazard and changes in the international geopolitical environment, indicate clearly that this risk (i.e., ID1) is *likely* to increase with time, though with the recovery from COVID-19, were it to focus on resilience-building, it is conceivable the risk could decrease over time, under lower climate change scenarios. Today's risk is assessed with medium confidence, based on the evidence in the literature. Future risks are assigned through expert judgement.

Whilst the observed evidence for food safety and quality impacts in the UK is less strong, the causal mechanisms and pathways are clear, and examples of these risks have been observed outside the UK (see e.g., CCRA2 Chap7). Increases in these risks are therefore also extremely likely.

## 7.2.2 Extent to which current adaptation will manage the risk (ID1)

### 7.2.2.1 Effects of current adaptation policy and commitments on current and future risks (ID1)

The observed evidence presented in section 7.2.1 shows that food shocks arise from the interaction between climatic hazards and a range of other drivers/events (for example via social amplification arising from the perception that a climate hazard will lead to food shortfalls). Whilst there are many ways that our current food systems can respond to events, adaptation to date has largely occurred autonomously - as a consequence of market actors reacting to events (EU-Exit planning, the 2007/8 food price spike, COVID-19, etc.) – rather than strategically, from consideration of the need for a resilient system. The Government’s Second Climate Change Risk Assessment (HM Government 2017), in response to the CCRA2 Evidence Report, indicated that food security planning included (a) disaster response planning, (b) investment in sustainable intensification to maximise local supply, and (c) an expectation that the market would manage the rest. The Government disagreed with the Evidence Report’s assessment that targeted government intervention was required to manage food price spikes, particularly to protect vulnerable people.

In the 2018 Cabinet Office Resilience Sector Plans (Cabinet Office, 2018), the Government set out how it and the sector will work together to ensure the resilience of the UK food supply. This builds on research into the resilience of food supply and building resilience in supply chains to extreme weather events. Food supply is also included as one of the 13 Critical National Infrastructure sectors. The second National Adaptation Programme (NAP2) stated that Defra would produce an annual Sector Resilience plan and carry out a review of the UK Food Security Assessment, which was due to be published in 2019 but has not yet appeared. Climate change is expected to be considered and highlighted as a risk (and possible opportunity) in this review (Watkiss *et al.*, 2019).

More broadly, there are efforts to adapt food systems to climate change, though their focus has primarily been on ensuring agricultural adaptation to climate change. These will have varying degrees of success across different locations and agricultural systems (Dinesh *et al.*, 2017). The international dimensions of such systems include those areas where global coordination is required. For example, addressing the risk of emerging pests and diseases with future climate change requires a globally consistent monitoring and management strategy, given the important role of transport and the global supply chain in the transmission and emergence of new pests and diseases (Bengyella *et al.*, 2017). From a system perspective, vulnerability to emerging pests and diseases with climate change is heightened when countries are highly reliant on imports from single countries, implying strategic market and production diversification policies could have co-benefits for importing countries vulnerable to market price spikes and supply shortages in their exporting countries (Lee *et al.*, 2018).

#### 7.2.2.2 Shortfall in current adaptation (ID1)

The food system is fragile and focus on “efficiency of supply chains” removes redundancy, centralises supply networks, removes diversity and reduces flexibility, all of which can act to reduce system resilience (see below, and Benton, 2020b).

The emergence of COVID-19 may have been influenced by disruption, from climate change, of ecological systems (Box 7.1). It is also an exemplar of climate-related hazards that include changing patterns of weather, sea-level rise, and ecological disruption due to climate that changes the incidence of pests and diseases (Bebber *et al.*, 2013). The COVID-19 pandemic caused a demand-side food shock in the UK and elsewhere, that has in some cases impacted on supply (for example, centralised food processing facilities having to close – e.g., meat packing plants – or transport interruptions creating a lack of input availability for planting in sub-Saharan Africa) (OECD, 2020a). Our view is that recent events have demonstrated the shortfall in resilience planning for food systems, for different reasons but similar outcomes as was highlighted in the CCRA2 Evidence Report.

The role of markets and trade in managing risks is a key area where coordination, or lack thereof, and international politics will play a critical role. In an ideal world, it is a tenet of trade theory that open markets are better at buffering shocks, e.g., Dithmer and Abdulai (2017). However, fully open markets are increasingly unlikely in the modern geopolitical world, where the post-WW2 architecture of rules-based international cooperation has been eroded (Benton, 2019; Biscop, 2016). In some countries that fear disruption from food insecurity, and the political fallout this causes, there is internal pressure to close borders to exports of food. This increases the risk of a global market shock through decreasing the availability of commodities globally (Brown *et al.*, 2017; Jones and Hiller, 2017), and which may have significant repercussions for the countries originally banning exports. Nonetheless, in 2007/8, 2010/11, and most recently in 2020, some governments did just this, for a range of political reasons (Bailey *et al.*, 2015; IFPRI, 2020).

At the time of writing, no further UK Government plans or policies on this topic have been announced, leaving a gap in adaptation action. It is our view that any expectation that the private sector will fill this gap is unlikely to be realised. Actions being taken to build the resilience of food supply chains have to date mostly been deferred from the public to the private sector. Businesses will take adaptation actions when the benefits of doing so outweigh their private costs (Cimato and Mullan, 2010), however, the great complexity of supply chains combined with the uncertainty around climate change impacts, suggests that the private sector might not take all appropriate actions (Watkiss *et al.*, 2019).

Market mechanisms, mediated by trade, buffer relatively small impacts of risk cascades, but any significant event (or coincident impacts in two breadbaskets) has the potential to lead to market failure (as per 2007/8 and 10/11). Unprecedented events are both difficult, and expensive, to plan for. Furthermore, market actors recognise that, in times of crisis, food security becomes an issue for the state and not market actors, which further disincentivises planning. Hence, the ‘adaptation gap’ (as highlighted in the CCRA2 Evidence Report, where exemplars of potential adaptation strategies are made) remains.

It is also noted that the impact of EU Exit will have potentially significant consequences for policies in this sector: with new border arrangements and new trade relationships that potentially impact the availability and price of food. A House of Lords EU Committee 2018 report on ‘Brexit: food prices and availability’ calling on the Government to produce “a comprehensive food strategy” to ensure food security post-EU Exit (House of Lords, 2018).

### 7.2.2.3 Adaptation Score (ID1)

Table 7.4 Adaptation score for risks to UK food availability, safety, and quality from climate change’s impacts overseas	
Are the risks going to be managed in the future?	
UK	Partially (Low confidence)

### 7.2.3 Benefits of further adaptation action in the next five years (ID1)

COVID-19, as a systemic shock that has critically impacted on food systems, and an exemplar of some of the climate-related risks that may occur in future, highlights the need to consider food-system resilience as a guiding principle. This is recognised by Henry Dimbleby and the National Food Strategy’s (NFS) first report (Dimbleby, 2020):

*‘There is a lot of work to do if we are to rebuild a food system that delivers safe, healthy, affordable food to everyone; that is a thriving contributor to our urban and rural economies; that restores and enhances the natural environment for the next generation; that is built upon a resilient, sustainable and humane agriculture sector; and **that is robust in the face of future crises.**’* (Dimbleby, 2020, National Food Strategy Part One, P.17, emphasis ours)

In particular, there is a need (as acknowledged in the NFS part 1) that due consideration given to a range of aspects within emerging Free Trade Agreements, post EU-Exit. As highlighted in a Chatham House report (Benton *et al.*, 2019), lack of consideration of potential environmental governance and exposure to climate risks could undermine the ability to have a resilient food system as climate risks mount. In addition, there is the potential for a reduction in UK agricultural resilience if lowering of production standards became necessary to compete with cheaper imports. Finally, FTAs through affecting prices and price resilience have potential impacts on UK food insecurity, especially for the marginalised groups, as noted in NFS.

A recent CCC outcomes study (Watkiss *et al.*, 2019) suggested that the Government could play a role in removing some of the barriers for the private sector to encourage climate change adaptation. Simultaneously, this private sector support could ensure a higher level of resilience along supply chains. Since many supply chains have international dimensions, a multi-national regulatory



structure in the food commodity markets, which are most vulnerable to climate-related supply-side shocks, could play a beneficial role. Further development and uptake of insurance instruments that protect both domestic and international actors in food supply chains would also contribute to adaptation. A greater focus on adaptive management, research, and learning in this sector would contribute to a more resilient food system. For example, identifying regions/countries which already show vulnerability to weather events, food production, and transport disruptions, and understanding how these vulnerabilities might change under different climate scenarios. This would help to understand the scale of the future vulnerability of the UK market and provide a stronger rationale for action (Watkiss *et al.*, 2019).

Populations at highest risk of lack of economic access to food are concurrent with those at risk of obesity and malnutrition (Drewnowski, 2012; Jones *et al.*, 2014b, Food Foundation 2017). Therefore, addressing food access inequality, access to fresh produce, and informed dietary choices, will likely have the co-benefit of reducing vulnerability to the risk of decreasing nutritional quality of food produced due to climate change.

### 7.2.3.1 Indicative costs and benefits of additional adaptation (ID1)

There are some aspects of climate change risks and responses that have been quantified for food supply chain resilience, but there is little information on the associated costs and benefits (in aggregate). Watkiss *et al.*, (2019) for the CCC reviewed the available options and provided some qualitative analysis of possible costs and benefits. This indicates a range of low-regret options, as well as some additional options to start the process for planning for these risks.

### 7.2.3.2 Overall Urgency Score (ID1)

<b>Table 7.5</b> Urgency score for risks to UK food availability, safety, and quality from climate change impacts overseas	
<b>Urgency Score</b>	More action needed
<b>Confidence</b>	Medium

The urgency score for this risk is that more action is needed (Table 7.5). Evidence for the urgency of dealing with this risk has increased since CCRA2 for two reasons: first, there is more evidence of specific events and their impact on food availability and food prices; and second, the growing academic evidence that there is a fundamental lack of systemic resilience (Nystrom *et al.*, 2019) has been brought into sharp focus by planning for the potential shock of EU Exit (particularly the recognition it brought about fragile supply chains for food and medicine), and by the actual shock to the global system arising from the COVID-19 pandemic.

### 7.2.4 Looking ahead (ID1)

As discussed in multiple places above, the current assessment is that hazards, exposure, and vulnerability to food shocks are increasing, but beyond that, the radical uncertainty of how societies

and economies will be in decades ahead means a prediction of how they will develop is extremely difficult. However, what is clear is that food system resilience is likely to grow in importance if climate changes impacts accelerate and if the recent trends away from global cooperation and geopolitical stability continue.

## 7.3 Opportunities for UK food availability and exports from climate change impacts overseas (ID2)

Global patterns of climate change can alter the comparative advantage of the UK in producing and trading in food. Climate change is one of a number of drivers that has an impact on food production patterns, through changes in productivity (e.g., higher or lower yields) and/or changes in the land suitable for producing food. The impact of climate change on global production patterns depends upon the relative importance of extreme events versus more gradual changes in climate, which may vary geographically. For example, new areas may open for production as a result of gradual warming, so long as extreme events do not disrupt agriculture and productivity.

On balance, the lack of evidence of global yield increases in response to climate change, and difficulties in the use of marginal land and water management suggest that food production opportunities will not be the norm (Challinor *et al.*, 2014). There are, however, opportunities associated with other drivers of international food systems, not least the ongoing trend towards plant-based meat substitutes and plant-based diets, which have the potential to both mitigate climate change and result in healthier diets.

### 7.3.1 Current and future level of opportunity (ID2)

#### 7.3.1.1 Current Opportunity (ID2)

Whilst realising any opportunity would require advanced planning, this opportunity is by nature long-term.

#### 7.3.1.2 Future Opportunity (ID2)

Climate change will alter global patterns of food production, creating, at least in theory, new opportunities for imports and/or exports. It may also increase the production of the current food-producing areas worldwide. CO<sub>2</sub> fertilisation is often cited, alongside longer growing seasons, as a reason to expect yield increases under climate change. However, when Iizumi and Ramankutty (2016) investigated the impact of CO<sub>2</sub> alongside other drivers of observed yield, by using simulations to attribute historical yield changes, they found that climate change has decreased the global mean yields of maize, wheat, and soybean. Similar results were reported for yield projections by Ostberg *et al.* (2018) and Shindell (2016).

The lack of observational evidence for global-scale net benefits of climate change on yield suggests that even where models project crop yield increases, results should be interpreted with some

caution. CO<sub>2</sub> fertilisation is often a key factor in such projected increases; yet the effect of elevated CO<sub>2</sub> relies on sufficient crop nutrients and water, which in practice often limit yield increases (Pleijel *et al.*, 2019; Schleussner *et al.*, 2018). Asseng *et al.*, (2019) used models to project global wheat grain and protein yield out to 2050 and found that both reduced, despite elevated CO<sub>2</sub>.

Model projections provide another way of assessing the potential for productivity increases globally due to climate change. Results suggest that increases will not be the norm (see section 7.3). Hence, overall, there is little evidence, from observations or models, of anthropogenic climate change causing increases in food availability to the UK. One, at least partial exception, is fruit and vegetable productivity, where there is some evidence to suggest climate-induced increases in productivity. Increases in minimum temperatures will lead to reduced risk of frost (Parajuli *et al.*, 2019); but also reduced winter mortality of pests (Gruda *et al.*, 2019). Another exception could be pasture and forage, where higher temperatures and CO<sub>2</sub> may lead to an increase in dry matter, thereby improving livestock production (Martinsohn and Hansen, 2013; Holden and Brereton, 2002). Through Northern Europe, the potential rainfed grass yield will increase (~14%) (Höglind *et al.*, 2013), mainly as a result of increased growing temperatures. Mauser *et al.* (2015) identified the potential for cropland biomass to be used to meet future biomass demand. Whilst there is significant potential, realising it relies upon increased cropping intensities (which in many cases would lead to increased emissions) and spatial reallocation of crops. Furthermore, the extent to which production is determined by mean changes in climate vs extreme events and variability is a key factor in determining the sign of that change. Currently, extreme events dominate, as outlined in section 7.3.

Any increases in productivity do not automatically translate into increases in food availability, which is the result of multiple climatic and non-climatic drivers, including the balance of supply and demand that determines where food is grown; the extent to which adaptation keeps up with climate change; and the course of international trade, as determined by business and by international politics (see sections 7.7 and 7.10). For example, in the case of meat and dairy 26% of all UK imports (by value) come from Ireland, 17% from the Netherlands and, 10% from Germany, which are therefore very important for UK unprocessed meat and dairy. If there are increases in pasture and forage productivity in these regions then, subject to the multiple drivers of production, this may result in greater availability of produce for UK import.

The balance of trade is determined in part by comparative advantage. If longer-term climate change results in a comparative advantage for UK agriculture relative to other food-producing regions, then there will be opportunities for increased exports (Hristov *et al.*, 2020; Watkiss *et al.*, 2019). However, as highlighted in CCRA2 Chapter 7, these opportunities come with a risk of unsustainable intensification of production. The issue of changing comparative advantage is particularly salient in the context of the Net Zero target, as noted below.

In addition to increases in productivity, there is a second pathway through which climate change can increase food production. New land may become available for food production overseas. Indeed, evidence of the potential for agricultural expansion has been broadly corroborated since CCRA2. Zabel *et al.* (2014) predicted agricultural land increases of 4.8 million km<sup>2</sup> for 2071-2100 under a SRES A1B scenario, due to increased area of suitable land. However, most of this land is 'marginally

suitable' and the estimated cropland expansion could take place in many highly biodiverse regions. Additionally, recent evidence suggests that most of the newly gained areas are subject to high interannual and sub-seasonal variability in water balances (King *et al.*, 2018). Further, larger areas of marginal land will need to be used if production is to be expanded to the newly available climatic regions (Fodor *et al.*, 2017). Despite these issues, there is some recent evidence that suggests that European and North American consumers might benefit from lower food prices under cropland expansion, whilst developing tropical regions will suffer from decreased biodiversity resulting from the expansion (Zabel *et al.*, 2014).

The analysis presented here so far has focussed on the beneficial effects of climate change, with the potential knock-on effect of increased food availability via increased imports. There is also the possibility that climate change's impact overseas may bring increased export opportunities. Where climate affects overseas production adversely, the UK may be able to make up shortfalls if production is maintained in the UK (see risks and opportunities for agricultural production in risk N6). It is theoretically possible, for example, that extreme events could provide an opportunity for increased exports in the face of a food shock overseas. However, the evidence for this is not conclusive: three years in the period 2000-2013 were identified in IPCC AR5 Porter *et al.*, 2014) as having significant climate-induced negative wheat production anomalies (Australia 2002 and 2006; and Russia 2010). The three years in which these production shocks occurred rank as the 2<sup>nd</sup>, 7<sup>th</sup>, and 6<sup>th</sup> largest UK wheat export volumes<sup>4</sup> in the 13-year period. Thus, this simple analysis (which ignores food quality and price competitiveness) reveals no evidence that production shocks overseas lead always to increases in UK exports. There is stronger evidence for a converse effect: anomalously high yields overseas can provide an opportunity for cheaper food in the UK, via global market mechanisms<sup>5</sup>.

#### 7.3.1.3 Lock-in and thresholds (ID2)

The UK does not have a major role in determining the extent to which other countries take advantage of changing climates. There is robust evidence with high confidence that global food production will decrease with increasing global mean temperature (see introduction to ID1). Supply chain lock-in issues do exist. New fixed trade agreements resulting from EU Exit, or COVID-19 disruptions could result in lock-in to international supply chains that fail to take advantage of any changes in food availability due to climate change.

#### 7.3.1.4 Cross cutting risks and Inter-dependencies (ID2)

There is significant interaction of this opportunity with the status of trade between the UK and rest of the globe. This opportunity overlaps with the risk in ID1 above.

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<sup>4</sup> <https://www.statista.com/statistics/299768/wheat-uk-exports-united-kingdom/>

<sup>5</sup> <https://www.worldbank.org/en/news/press-release/2015/07/01/global-food-prices-drop-to-a-five-year-low>

### 7.3.1.5 Implications for Net Zero (ID2)

There are also implications for the net-zero target: emissions scenarios are sensitive to assumptions about UK food production and the current CCC analysis (CCC, 2020) assumes domestic production stays constant (whereas it may grow, or shrink, in the future depending on demand and changing policy and market environments post-EU-exit). Potential changes in emissions due to responses to international climate risks and opportunities include changes in transport, via the movement of goods transmission pathway, due to changes in imports and exports.

### 7.3.1.6 Inequalities (ID2)

As mentioned, higher yields overseas could lead to cheaper food in the UK and therefore making food increasingly accessible. It is not clear how this opportunity may benefit some groups more than others. For example, increasing commodity crop production (sugar, oil, starchy grains) could lead to higher consumption of cheaper highly processed foods by the economically marginalised, leading to a greater burden of non-communicable disease. Conversely, greater availability of fruit and vegetables may have the opposite impact.

### 7.3.1.7 Magnitude Scores (ID2)

<b>Table 7.6</b> Magnitude score for opportunities for UK food availability and exports from climate change impacts overseas					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>UK</b>	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Low  (Medium confidence)

Whether or not any import or export opportunities are realised depends upon whether and how food production is translated into increases in food availability. On balance, increased productivity forms a minority in the projections of climate change impacts. Further, there are thresholds above which food production decreases (see section 7.3). The lack of evidence of global yield increases, and the difficulties, outlined above, in the use of marginal land and in water management suggest that food production opportunities will not be the norm. Hence there is medium confidence that opportunity ID2 is of low magnitude for all climate scenarios.

### 7.3.2 Extent to which current adaptation will manage the opportunity (ID2)

#### 7.3.2.1 Effects of current adaptation policy and commitments on current and future opportunities (ID2)

It is unclear what actions are currently planned on trade policy for the next five years that might act to take advantage of any benefits from climate change on UK agricultural production. Changes to imports and exports will no doubt occur under EU Exit and it may be that opportunities for UK food availability and exports from climate impacts overseas are not high on the agenda. The agility of businesses to respond to EU Exit will perhaps also be an indicator of the ability to respond to climate impact opportunities in the future if these arise.

#### 7.3.2.2 Shortfall in current adaptation (ID2)

Taking advantage of any specific opportunities that do emerge from long-term climate change relies on viable access to international markets. For example, with access to the right markets, the UK might export more to the southern EU (as documented on page 27 of CCRA2), or to other parts of the world (Hristov *et al.*, 2020), in order to compensate for regional deficits. More evidence for opportunities for export to the southern EU has been produced since CCRA2 (e.g., Fronzek *et al.*, 2019).

Statements on specific further action on this opportunity are difficult to make since the extent of planned actions is unclear. In broad terms, actions over the next five years could usefully focus on access to a broad range of international markets, via goods, finance, and markets transmission pathways, in order to ensure that opportunities can be capitalised upon.

Statements on actions regarding the sourcing of food are also extremely difficult to make. Even if – contrary to the most likely scenario indicated here – there were a detectable increase in food availability due to climate, ongoing changes in trade agreements and policy, as discussed in section 7.9, are likely to be far more important in determining where food is sourced. Thus, the evidence suggests that this opportunity does not need further action in the next five years.

#### 7.3.2.3 Adaptation Score (ID2)

Table 7.7 Adaptation score for opportunities for UK food availability and exports from climate change impacts overseas	
Are the opportunities going to be managed in the future?	
UK	Yes  (Medium confidence)

### 7.3.3 Benefits of further adaptation action in the next five years (ID2)

#### 7.3.3.1 Indicative costs and benefits of additional adaption (ID2)

As reviewed in section 7.4.2, ensuring access to a broad range of international markets would capitalise on any opportunities associated with climate impacts overseas. There is no evidence to suggest further actions that would support such opportunities. Access to markets, which was covered in some detail in CCRA2 Chapter 7, has the co-benefit of providing some resilience to external shocks, be they climate-induced, or sourced elsewhere (e.g., a global health disruption such as COVID-19). Hence there are multiple lines of reasoning that suggest benefits of access to markets.

#### 7.3.3.2 Overall Urgency Score (ID2)

<b>Table 7.8</b> Urgency score for opportunities for UK food availability and exports from climate change impacts overseas	
<b>Urgency Score</b>	Watching brief
<b>Confidence</b>	Medium

The urgency score for this risk is for a watching brief (Table 7.8). The evidence reviewed above suggests that, whilst actions to increase access to markets produce clear benefits, the opportunities associated with climate impacts overseas are not, in and of themselves, sufficient cause for such actions.

### 7.3.4 Looking ahead (ID2)

Global food production patterns are important for reasons well beyond any opportunities they might afford to the UK. Numerous drivers determine the global situation that may or may not give rise to opportunities associated with climate impacts overseas. As was noted in some detail in CCRA2 Chapter 7, these changes have the potential to improve the health of the UK population whilst also reducing emissions. Demand for plant-based meat substitutes is growing globally (Curtain and Grafenauer, 2019) and there is evidence also of growth in plant-based diets in high-income countries (Medawar *et al.*, 2019). If these trends continue then they will eventually alter the patterns of global food production. If these changes are planned well, they will result in a reduction in emissions (IPCC, 2019).

## 7.4 Risks and opportunities to the UK from climate-related international human mobility (ID3)

Negative climate change impacts will make some places more difficult to live in and could undermine the development gains overseas in which the UK has invested. One potential adaptation is displacement and migration (see framework movement of people transmission pathway). Affected areas are most likely to be areas in the Global South exposed to frequent climate extremes with high dependence on agriculture and weak social safety nets. Unplanned, unsupported, and precarious climate migration presents risks to the human rights of the people on the move, as well as their wider social and economic opportunities. Most climate-related migration in the near future will be domestic, within affected countries or regions. Thus, the UK is unlikely to be a major migrant-receiving country. Evidence of negative socio-economic impacts or security threats associated with migration is weak. For example, impacts of migration on the labour market of the receiving country or area, are negligible or net positive (Dustmann and Frattini, 2014).

Where migration to the UK does increase due to socio-economic, political, and environmental change, climate will be one of many drivers of migration, and migration will take place along existing routes. However, increased mobility as a result of climate change is likely. Where people are on the move between regions overseas, there are risks to the well-being of those individuals and as such the potential to undermine development gains overseas (as described in CCRA2; and evidence since further supports this finding). However, there is little evidence to suggest that there will be knock-on risks to the security of the UK, for example, through migration leading to conflict. Adaptation to this risk involves ensuring pathways for regular migration and working to alter negative perceptions of migration in receiving countries alongside supporting development, infrastructure, strong institutions, and transparent decision-making in other countries. Future increases in migration overseas as a result of climate instability present a socio-economic opportunity if migrants are supported in integrating effectively into the host society.

The weather usually affects migration indirectly through its impact on natural-resource dependent livelihoods such as agriculture (e.g., Kubik and Maurel, 2016), or directly through displacement from extreme events such as floods and tropical storms (e.g., Islam and Shamsuddoha, 2017), coupled with a lack of adaptive capacity. These are often experienced together, for example, sea-level rise is a slow onset event that will also worsen coastal hazards - increased flooding, erosion, salinization of agricultural land and freshwater aquifers, and eventual inundation (Hauer *et al.*, 2020). Most climate-related migration is internal to the affected country since crossing international borders is financially and emotionally expensive (Kaczan and Orgill-Meyer, 2020). While there is always an element of choice in migration, the imperative to leave tends to be stronger and more urgent in rapid-onset events (i.e., when cyclones threaten lives, property, and key infrastructure) while the climate becomes part of economic concerns in slow onset events (i.e., when changing precipitation regimes lead to a decline in agricultural productivity). The duration of migration will also vary depending on the cause of migration.

Resettlement due to widespread damage after extreme weather, or in anticipation of places becoming uninhabitable, is another mobility response that involves whole communities moving



together usually with assistance from external institutions. Resettlement prior to the onset of the worst climate impacts is preferable because it ensures that communities remain together and can move in a way that preserves valued practices. Resettlement mostly leads to negative well-being outcomes for the population, but impacts are fewer if resettlement is voluntary and affected communities are involved in decision-making (McMichael *et al.*, 2019).

The anthropogenic element of the environmental hazard is difficult to attribute, that is to say, how much of increases in intensity or frequency of extreme weather is attributable to climate change. However, the influence of climate change is likely to increase as climate change accelerates over the next few decades. Lack of attribution does not have to act as a barrier to interventions, because interventions in this area will have broad positive development outcomes (Schwerdtle *et al.*, 2018). While a relationship between environmental change and migration is well-established, the nature of that relationship is context specific. This is due to the social, economic, cultural, and political context that mediates the impact and response, and the multi-causal nature of migration which is always the result of multiple drivers (Black *et al.*, 2011). This also means that the proportion of migration driven by environmental factors is difficult to isolate. The type of migration outcome from climate impacts depends on the characteristics of the weather event, the socio-economic and political conditions, and the level of assets of the household (Cattaneo *et al.*, 2019). Environmental change can lead to an increase in migration as people leave to find alternative income opportunities, can decrease as people lose the capital required to fund migration, or can change its characteristics, for example, flows may be gendered as men are generally more able to take up migration opportunities (see Kaczan and Orgill-Meyer, 2020 for a review).

Research since CCRA2 has furthered our understanding of when migration can be considered a successful adaptation to climate change. That is to say when it increases the well-being of those involved. Levels of income, assets, and networks vary, altering people's ability to adapt *in situ* to climate impacts and thus their need to migrate, as well as their ability to migrate in a manner that reduces their vulnerability. Migration that takes place under duress in conditions of stress (i.e., distress migration) rarely increases the well-being of the migrant or their family and tends to only perpetuate or worsen conditions (Natarajan *et al.*, 2019). Households with higher income have more choice (Adams & Kay, 2019) having both higher capacity to make adaptations that allow them to stay in location, for example, by adapting their income source, but also to access better opportunities through migration (Riosmena *et al.*, 2018). At the other end of the spectrum are households that, due to insufficient capital, are unable to adapt *in situ* or migrate and live in areas exposed to climate risk and are highly vulnerable with low adaptive capacity (Suckall *et al.*, 2017).

Thus, adaptation to climate migration involves improving policy responses on migration to support people in their migration choices, or lack thereof (Wrathall *et al.*, 2019) and facilitating translocal lives, where people are active in the social, political, and economic spheres of two different places through travel and telecommunications and facilitating diverse mobility responses that increase resilience (Porst & Sakdapolrak, 2018).

Discussions on how to support climate-related migrants are occurring in the context of an increasingly bordered world (McLeman, 2019). Migration is often conceptualised as a threat to national security in media and policy discourses, but this characterisation tends to depend on often

incorrect perceptions and cultural stereotypes, for example, the perceived negative impact of immigrant labour on employment (Wallace, 2018), an association made between terrorism in the EU and migrants (Bove & Böhmelt, 2016), and perceived threats to a race-based national identity (Rudolph, 2006; Fassin, 2011). Migration is rarely an economic threat as migration has been shown to have extremely small impacts on wages and employment rates (Docquier *et al.*, 2019). Future, border policies, policing, and physical barriers to prevent migration tend to be symbolic, rather than effective at preventing irregular migration (Slaven & Boswell, 2019). Should immigration to the UK increase, and thus the movement of people transmission pathway, as a result of climate change disruption overseas, our assessment is that the risks lie in failing to maximise on potential opportunities, rather than in avoiding any security risk. Whether migration becomes an issue for the UK depends on policies put in place to promote regular migration and facilitate positive public attitudes to diversity and inclusion. This allows the Government to manage social amplification or attenuation of risk, and issues arising from the perception of migrants as a security risk.

International travel is costly and requires certain levels of human (e.g., education, ability to navigate border/visa requirements) and financial capital (e.g., for flights, visas, to pay smugglers). Where international, displaced populations will move to countries with contiguous borders or countries where there are already established migrant corridors, transport links, and low institutional barriers (e.g., visa waivers) (Veronis *et al.*, 2019). The evidence for climate-related international migration, where occurring, is within the regions of sub-Saharan Africa and South Asia (Obokata *et al.*, 2014, Veronis *et al.*, 2018) with climate as one contributing factor among political and economic drivers. Thus, where international migration to the UK does occur, it is likely to be the endpoint of sequential migration and migrants are likely to be professionals able to meet visa requirements. There are a handful of studies since CCRA2 that have found a correlation between negative climate impacts and low-to-high income country migration (e.g., Coniglio and Pesce, 2015) and asylum applications (for example, for a period during the Syrian conflict (Abel *et al.*, 2019). However, associations do not hold outside the particular dataset and time period and so cannot be generalised (Mach *et al.*, 2020). There are a few studies qualitative studies exist that have discerned a climate factor in economic decisions to migrate from low to high-income countries (McLeman *et al.*, 2018).

## 7.4.1 Current and future level of risk and opportunity (ID3)

### 7.4.1.1 Current Risk (ID3)

The equivalent risk to this one in CCRA2 was “Risks to the UK from climate-related international human displacements”, and it assessed the risk of climate change undermining development progress through the impact of extreme weather events overseas. Based on the improved understanding of responses to fast and slow onset events, we find here that there is a broad range of human mobility responses, including migration, displacement, and resettlement. These act across continuums of both forced to voluntary, and short to long distance.

CCRA2 Chapter 7 found that displacement due to extreme weather had significant potential to affect UK’s interests overseas by undermining development efforts, on which the UK has made significant expenditure (Challinor *et al.*, 2016). Further, the report concluded that extreme weather (including

wildfires) has a negative effect on the health and well-being of those exposed and those forcibly displaced by climate-related hazards. These risk drivers continue to be important. Since CCRA2, damage from cyclones and tropical storms globally has continued unabated, with the evidence suggesting an increase in the intensity, frequency, and scale of loss from extreme weather events and their interactions (AghaKouchak *et al.*, 2020; Coronese *et al.*, 2019) as well as the potential for shifts in the regions that are habitable for humans (Xu *et al.*, 2020).

Whilst the risk drivers have increased, since CCRA2 there have also been significant changes in global border regimes, and thus the movement of people transmission pathway, that may impact this risk. On one hand, there has been an increased focus on closed and protected border regimes where migrants are more likely to be represented as a national security threat. This has occurred in places like the US-Mexico border, the Lebanese-Syrian border, and the Turkish-Greek border. The EU has strengthened the powers of Frontex, its border agency, and EU countries have made various bilateral agreements to try to close migration routes from North Africa to Europe (Bialasiewicz, 2012). Since the previous report, the UK has implemented a series of policies to reduce the ease of migration to the UK (Webber, 2019). For example, requiring proof of residence to take up work, rent property, or make use of the NHS. Since the UK began its process of leaving the EU, citizens from the EU have had to apply for residency status.

On the other hand, there is increased global collaboration on migration, and consensus on the need to take a human-rights' centred approach to migration, exemplified in the United Nations Global Compact for Safe, Orderly and Regular Migration (The Global Compact). The United Nations Framework Convention on Climate Change at its Conference of Parties (COP) in Paris in 2015 established a Displacement Task Force to "develop recommendations for integrated approaches to avert, minimize and address displacement related to the adverse impacts of climate change" (Decision 1/CP.21) (UNFCCC, 2016). These processes may provide a framework for international cooperation on climate-related migrants into the future.

#### 7.4.1.2 Future Risk (ID3)

In the longer term, climate change will alter the relative habitability and attractiveness of different places and thus change the size and direction of flows. For example, some areas of the Middle East and South Asia are experiencing extreme temperatures that make working outside a severe health risk (Kjellstrom *et al.*, 2016; Pal and Eltahir, 2016). Other places may eventually become more attractive, such as high latitudes when higher temperatures increase the agricultural potential and alter the geographical ranges of staple crops (Xu *et al.*, 2020). The result of these changes in climate is likely to be some global population movement (Xu *et al.*, 2020), but this relationship will be mediated by social factors such as deepening inequality, a globalised economy, increased connectivity through telecommunications and air travel; and other causes of human mobility such as political instability and oppression, conflict and low levels of development. Climate change will act as a threat multiplier for other processes that make places less attractive, for example, through its interactions with armed conflict (Braithwaite *et al.*, 2019).

The UK's exit from the EU will shape relationships of England, Scotland, Wales, and Northern Ireland, where there already can be a disconnect between responsibility for welfare and integration of

migrants and asylum seekers (which fall under the remit of the administrations) and UK immigration policy (Mulvey, 2015). Further, internal mobility within the UK is relatively unresearched and has implications for responding to any potential increase in migration in the longer term. For example, asylum seekers are sometimes dispersed throughout the UK and minority ethnic groups (both British and non-British born) have different mobility patterns to their UK counterparts (Darlington-Pollock *et al.*, 2019).

In terms of the migration patterns of those who have come to the UK, studies show the negative impact of different policy approaches of the devolved administrations on their ability to successfully integrate asylum seekers, for example, differences between devolved administrations housing health and immigration policy (Mulvey, 2015). The Foresight report in 2011 highlighted the potential benefit to all nations of supporting safe and orderly migration that maintains the dignity of the migrant. Thus, there is an opportunity for the UK to establish procedures to ensure that any increases in migration are beneficial to the nation. Second, there are win-win opportunities ensuring that overseas development and humanitarian response empower local communities such that they are not forced to migrate.

Likewise, internally to the UK, there will be new dynamics with the UK's overseas territories, most of which are island nations exposed to the impacts of climate change with their own set of vulnerabilities, relating to, for example, asymmetrical governance structures (Petzold and Magnan, 2019).

#### 7.4.1.3 Lock-in and thresholds (ID3)

The UK will miss an opportunity if it is not able to maximise on the benefits that new migrants bring to the UK. Further, if the UK does not reinvest in social mechanisms that allow newcomers to integrate effectively into the job market and local culture there is the potential for negative repercussions in terms of social tension. The current political climate is not amenable to investing in consensus and community-building (Mulvey, 2015).

#### 7.4.1.4 Cross cutting risks and Inter-dependencies (ID3)

There are interacting risks with conflict, health, governance – diaspora populations, and tourists and health. Additionally, there are interacting risks with food availability, safety, and quality, which can cause climate migration.

#### 7.4.1.5 Implications for Net Zero (ID3)

There are limited implications for Net Zero related to this risk.

#### 7.4.1.6 Inequalities (ID3)

It is not fully clear how this risk may impact some groups more than others. Studies show that ethnic minority groups are less mobile than their white counterparts and non-UK born minorities are more likely to move at certain life stages, but this effect disappears once time spent in the UK is controlled.

## 7.4.1.7 Magnitude Score (ID3)

<b>Table 7.9</b> Magnitude score for risks and opportunities to the UK from climate-related international human mobility					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>UK</b>	Low  (High confidence)	Low  (Medium confidence)	Low  (Medium confidence)	Medium  (Low confidence)	Medium  (Low confidence)

The result of the above set of conditions is that our view is that the current risk of climate-induced international mobility causing issues for the UK is considered low, with high confidence (Table 7.9). Climate change will increasingly challenge overseas development gains and the welfare of individuals in other countries. Numbers of people on the move are likely to increase in the long term due to the destruction of property and livelihoods from extreme weather events and changes in agricultural productivity.

The UK is unlikely to receive many migrants as a proportion of the total, in the short-to-medium term. Those people that do arrive represent an opportunity, with the potential to meet skills shortages, for example, care workers associated with an aging population. Whether people on the move represents a risk to economic interests and social stability in the UK and its interests overseas depends on whether there are opportunities for safe and orderly migration, whether predominantly urban receiving areas in other countries are prepared (e.g., in terms of infrastructure), and effective governance structures are in place. The UK is entering into a period of unprecedented change in its international relations as it exits the European Union, while having also merged its foreign policy and diplomacy and international development departments into the Foreign, Commonwealth and Development Office.

In the long term, changes in the geographical ranges of staple crops have the potential to cause a significant redistribution of the population with associated increases in mobility (Xu *et al.*, 2020). While the UK will be the destination of very few of these migrants, changing population distribution overseas will likely have broader economic and geopolitical impacts relevant to the UK, although the academic literature is weak in this area due to issues highlighted earlier of projecting socio-economic change into the future. Thus, the risk to the UK in the longer term is Medium, with Low confidence.

## 7.4.2 Extent to which current adaptation will manage the risk and opportunity (ID3)

### 7.4.2.1 Effects of current adaptation policy and commitments on current and future risk (ID3)

The challenges posed by human migration to the UK are social issues to be solved through policy and planning. Issues created by people on the move relate to integration, assimilation into the job market, and ensuring sufficient services, infrastructure, and access to justice/legal proceedings in destination locations. Since most migration is internal or to neighbouring countries, impacts of any climate-related displacement are likely to be borne predominantly by the countries also experiencing the climate change impacts from which people are moving. These countries will most likely be low- to middle-income countries in the global South and as such are often beneficiaries of UK Official Development Assistance, referred to as the overseas aid budget.

Climate resilient development, adaptation, and appropriate disaster management and preparedness practices will go some way to preventing overseas development gains being undermined by worsening climate change impacts. However, there are limits to the ability of the UK's overseas aid budget to reduce the exposure of vulnerable populations to climate hazards such that migration is not required. Although an important element in overall UK Government spending, it is insignificant compared to the number of global poor who will face an adaptation gap, with current estimates of annual adaptation costs in developing countries of USD 70 billion, rising to 140-300 billion in 2030 (UNEP, 2018, UNEP 2021).

The UK has publicly committed to double its current ODA spend specifically intended to tackle climate change and help people adapt to its negative effects – the UK's International Climate Finance (ICF) - from £5.8bn to £11.6bn between 21/22 and 25/26. Although this is not all specifically intended to address migration issues and takes place within the overall context of reduced spend on ODA, the ambition to spend 50 percent on climate change mitigation and 50 percent on adaptation is welcome and will help improve peoples' resilience.

### 7.4.2.2 Shortfall in current adaptation (ID3)

Our view is that development that aims to stem migration by addressing the root causes of poverty or unemployment in traditional sending countries is likely to be unsuccessful at reducing any migration due to climate change. Development is suggested as a solution when migration is analysed in isolation rather than contextualised in wider processes of globalisation and other North-South relations such as labour markets and production demands that drive global migration patterns (Castles, 2004; Anderson, 2017). Such responses miss seeing migration as a social process with its own set of dynamics (Castles, 2004).

At present, there is no coordinated policy approach to adapt to this risk, to ensure receiving areas benefit from new migrants and to prevent migration undermining the wellbeing of those on the move. This would require embedding migration in broader international relations and ensuring migration priorities in the UK follow strategic priorities relating to different UK government policy objectives.

For the next five years however, strong adaptation is required in the UK to ensure that adaptation governance structures are in place internationally to ensure that people displaced by climate change overseas are able to move to seek alternative opportunities and that likely receiving areas (e.g., cities) are supported in planning for changes in population. Domestically, the UK can plan to take advantage of potential opportunities associated with increased migration to the UK.

#### 7.4.2.3 Adaptation Score (ID3)

<b>Table 7.10</b> Adaptation score for risks and opportunities to the UK from climate-related international human mobility	
<b>Are the risks and opportunities going to be managed in the future?</b>	
<b>UK</b>	Partially (Low confidence)

### 7.4.3 Benefits of further adaptation action in the next five years (ID3)

#### 7.4.3.1 Indicative costs and benefits of additional adaptation (ID3)

Any adaptation in the next five years would most likely involve protecting the human security of people on the move, and those in low-income receiving areas in the Global South, rather than on the national security of the UK. Solutions lie in creating safe pathways for migration, the movement of people transmission pathway, and helping the UK and other host countries to accommodate newcomers through education and language courses, training and retraining in skills relevant to the job market, planning for infrastructure and services in areas likely to receive migrants, as well as managing public perception of migration. Migration as an adaptive response, and a proportion of the population outside their places of origin, are constants of any society. Thus, opportunities lie in recognising the agency of migration and the novel forms of organisation and cooperation that emerge within migrant groups that have the potential to benefit the UK and its overseas interests (Papadopoulos & Tsianos, 2013; Stierl, 2018).

The Foresight report in 2011 (Foresight & Government Office for Science, 2011) highlighted the potential benefit to all nations of supporting safe and orderly migration that maintains the dignity of the migrant. In the context of the Lifetime Skills Guarantee the UK Prime Minister has highlighted skilled labour shortages, that could be filled with migration until filled domestically. Thus, there is an opportunity for the UK to set up procedures to ensure that any increases in migration are beneficial to the nation. Second, there are win-win opportunities ensuring that overseas development and humanitarian response empowers local communities such that they are not forced to migrate but have agency in if, when, and where they chose to move.

The Foresight follow-up report noted that different Government Departments were responding quite differently, thus there is the opportunity to create greater cohesion between departments. While there are several Cabinet committees dedicated to considering both domestic and

international issues, it appears that the membership of some of these committees could be more strategically focussed to tackle the linkages between climate and migration. For example, the overarching National Security Council chaired by the Prime Minister which inter alia considers ‘international relations and development’ included both the Home office and DFID (now FCDO). The Climate Action Implementation Committee included DFID but not the Home Office, while the Committee on Climate Action Strategy included neither DFID nor the Home office.

During the period immediately following the UK’s exit from the European Union there is a window of opportunity to provide pathways for safe and orderly migration to the UK. Migration decisions and migration flows are already mixed, and so climate migrants will come to the UK, not as a separate, easily defined group, but as economic migrants or potentially as asylum seekers. The UK can maximise the benefits that any new migrants bring and thus there are obvious benefits to the UK’s investment in social mechanisms that allow newcomers to integrate effectively into the job market and local society. The merger of DFID and the Foreign and Commonwealth Office (FCO) as FCDO, can provide an opportunity to develop more deliberate climate and migration policies with oversight from the most senior Cabinet Committees.

Monetised indicative costs and benefits of additional adaptation are not currently available at the time of writing.

#### 7.4.3.2 Overall Urgency Score (ID3)

<b>Table 7.11</b> Urgency Score for risks and opportunities to the UK from climate-related international human mobility	
<b>Urgency Score</b>	Watching brief
<b>Confidence</b>	Medium

The urgency score for this risk is watching brief (Table 7.11), due to our estimated low current and future risk of climate migration directly affecting the UK and migration as an opportunity rather than a risk to the UK. For this risk, indirect effects such as the role of social amplification remain important and require managing public perception of migration.

However, adaptation in terms of safe pathways for migration and accommodation of migrants does require attention. Since the publication of CCRA2, the risks posed by climate change to the well-being of climate-vulnerable populations forced to migrate in conditions of low agency and distress has not diminished. However, research has provided a better understanding of the complexity and diversity of migration as a response to climate change and the role of policy in ensuring that migration produces positive development outcomes in sending and receiving areas. At the same time, since CCRA2 a window of opportunity has opened to make such policy interventions with the exit of the UK from the European Union and the creation of the Foreign, Commonwealth & Development Office (FCDO). This further allows perhaps greater management of the public perception that migration is a significant risk to the UK.



#### 7.4.4 Looking ahead (ID3)

The UK is currently repositioning itself with respect to the European Union. Although the UK has never been part of the Schengen Area, EU Exit will have impacts on the countries from which the UK draws to meet labour shortages. This will evolve as the UK will develop relationships with countries outside of the EU. If UK labour shortages are met through non-EU migration, and especially, migration from the Global South, there could be an increasingly strong climate signal in economic decisions to migrate.

The merger of the UK's Foreign Office with the Department for International Development into FCDO will likely bring challenges as well as opportunities - for this risk and for other international risks covered in this chapter. Closer collaboration between the two Departments was already happening, especially in-country, but the merger has greatly accelerated that process. The mechanics of merging two organisations are not straightforward, will take several years to be fully implemented and risk diverting time and resources from the shared objectives of both. On the other hand, the greater financial and diplomatic reach of the combined Department could greatly enhance the impact of the UK's development efforts. Many of the climate related challenges for the Global South are intertwined with the policies and practices of the Global North as mentioned previously, not just the availability of finance, and so the international influence of the FCDO will be critical to achieving the UK's development objectives.

Since overseas development has the potential to reduce vulnerability and increase adaptive capacity to climate impacts and distress migration, then this UK shift in focus may have an impact on the way in which displacement and loss from extreme weather events and climate change translates into migration outcomes.

### 7.5 Risks to the UK from violent conflict overseas resulting from climate change (ID4)

Recent literature continues debating the role of climate change as a driver of conflict. Nevertheless, there is consensus in the recognition of climate as an amplifier of root causes for conflict, whilst also recognising that a range of other drivers affect the causal association between climate and conflict. These include, but are not limited to, pre-existing conflict (at local and country scales), level of democratisation, post-colonial transformation, economic context, and population growth. Overseas conflict can have an indirect impact on the UK through a variety of UK overseas interests, and various transmission pathways such as governance, people (migration), refugees, and finance and markets.

## 7.5.1 Current and future level of risk (ID4)

### 7.5.1.1 Current Risk (ID4)

Conflict – along with humanitarian assistance – is among the principal regions for the deployment of the UK military overseas. Climate change has important implications for the military, both in terms of the contribution to the direct issues underlying deployment (such as conflict), but also in the way that climate change may affect the functioning of equipment or personnel (e.g., heat stress), or even access to places where training can safely be conducted (IMCCS, 2020).

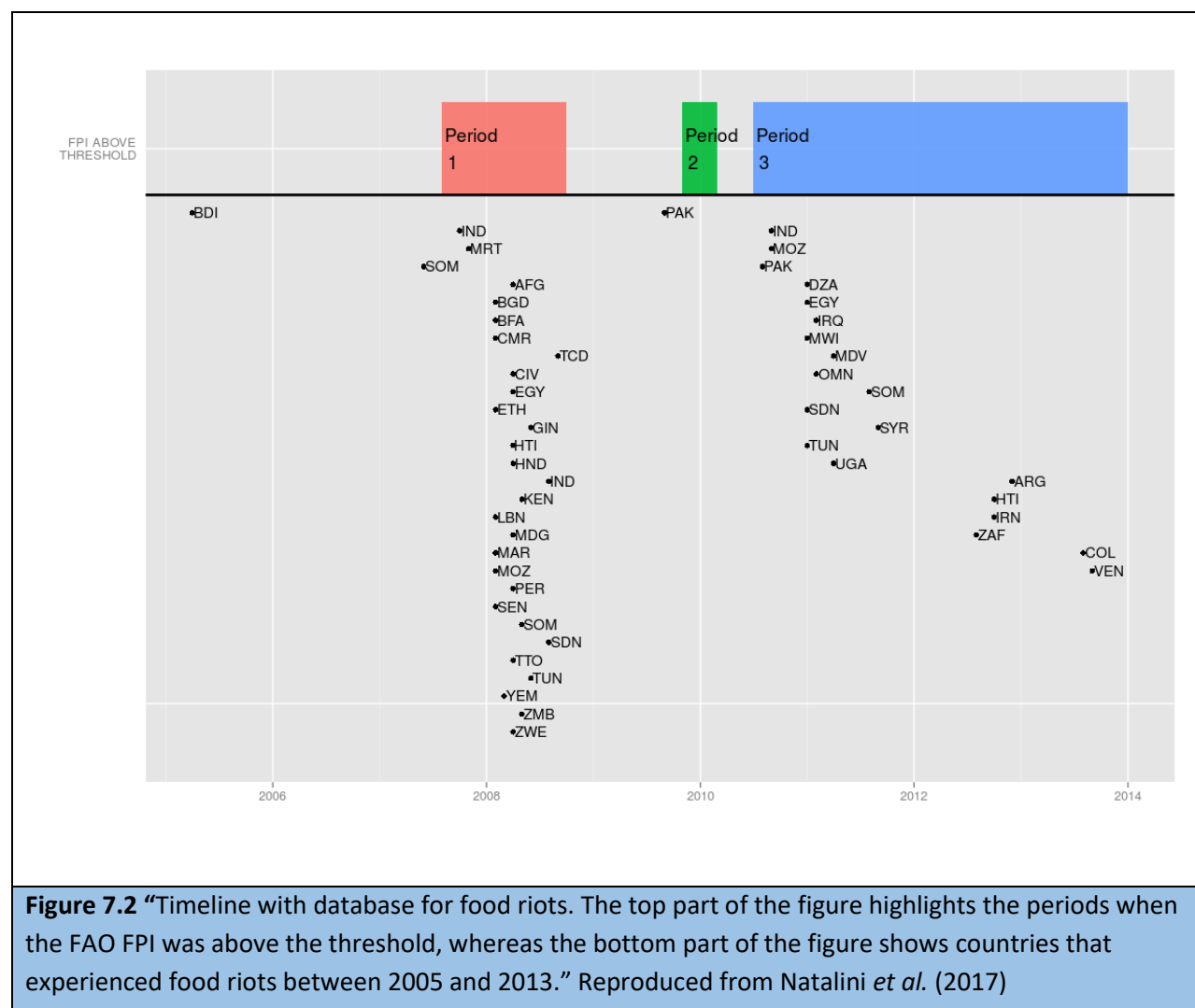
Recent literature (Levy *et al.*, 2017; Gilmore *et al.*, 2018; Sakaguchi *et al.*, 2017) continues debating the role of climate change as a driver of conflict. Nevertheless, there is consensus in the recognition of climate as an amplifier of conflict, whilst also recognising that a range of other drivers affects the causal association between climate and conflict (Peters *et al.*, 2020). These include, but are not limited to, pre-existing conflict (at local and country scales), level of democratisation, post-colonial transformation, economic context, and population growth (Harari and Ferrara, 2018; Owain *et al.*, 2018; Breckner, 2019) across a range of geographies.

Abel *et al.* (2019) corroborate findings of both Harari and Ferrara (2018) and Breckner (2019) that broad-scale drivers of the likelihood of conflict are pre-existing conflict, but also identify a higher likelihood of conflict in ‘medium-democratised’ governments compared to ‘full-democratised’ governments. In addition, as noted in ID3 environmental change can lead to the temporary or permanent displacement of people within countries, which in turn could increase the likelihood of conflict within countries through bad policy or planning. More generally, as noted in Section 7.5, conflict can lead to increased pressures elsewhere through processes including forced migration and refugees (Braithwaite *et al.*, 2019).

While interstate conflict has reduced over the last few decades *“the risks associated with climate-related disasters do not represent a scenario of some distant future. They are already a reality for millions of people around the globe – and they are not going away,”* Rosemary DiCarlo, the Under-Secretary-General for Political and Peacebuilding Affairs addressing the UN Security Council in January 2019 (UN News, 2019). For example, the conflict around Lake Chad has been, alongside other factors, linked to climate change and ecological changes (UN Security Council, 2017).

Extreme weather events can also be causally linked to conflict through the mechanism of food production shock (Headey and Fan, 2008; Headey and Fan, 2010). Food production shocks can also drive food price shocks (see ID1) and these food price shocks can lead to riots and unrest (Lunt *et al.*, 2016). The main drivers for food insecurity are long-term social trends (Puma *et al.*, 2015), however, extreme weather events driven by climate change can be a contributor to locally and globally significant shocks. For example, while the civil war in Syria has a number of complex interrelated factors *“water and climatic conditions have played a direct role in the deterioration of Syria’s economic conditions”* (Gleick, 2014, p.331) with a three-year drought preceding initial protests (Kelley *et al.*, 2015).

Food access and affordability for the poorest sections of society is a critical issue. Natalini *et al.* (2017) found that when the Food and Agriculture Organisations' global Food Price Index (FPI) went beyond a threshold of 140, food riots are more likely to occur. They found three periods where the FPI was above this level and that the vast majority of civil unrest events linked to food insecurity occurred during these periods (Figure 7.2). These riots can be globally significant and include the events that fed into the Arab Spring.



Breckner (2019) studied the impact of scale and found relationships between conflict and temperature to be significant when spatially and temporally disaggregated. High-resolution analysis of conflict and climate over Africa, found that temperature extremes (95th percentile deviation from the monthly specific mean in a given grid cell) are strongly and significantly related to an increase in the number of conflict outbreaks. She also found that the length of climate events was an important consideration; two-month events were more strongly related to conflict outbreaks than one-month events (Breckner, 2019). However, there is a complex relationship between conflict and temperature extremes, with socioeconomic factors playing an important part.

Harari and Ferrara (2018) contributed to developing more high-resolution analysis of conflict-migration-climate relationships, by using a 1-degree grid-scale, also over Africa, between years 1997 - 2011, applying Standardised Evapotranspiration Index (SPEI), an indicator of agricultural-drought, for the specific growing season of crops in each grid cell. They found there was a specific SPEI-conflict relationship at the local level, but that conflict also exhibits a 'persistence' across time and space. The likelihood of a conflict was more strongly related to a pre-existing (12% points increase in the likelihood of a conflict outbreak) or localised conflict (2.3% higher), than to localised agricultural shock (SPEI) (1.3 % higher).

The exact causal factors at play in these studies are highly contested. A self-reported limitation of these studies is that at a fine scale, the role of institutions is outside their system boundary, but may be of significant importance as a broader scale driver (Harari and Ferrara, 2018; Breckner, 2019). Mach *et al.* (2019) assessed the current understanding of the relationship between climate and conflict using assessment facilitators with a group of highly experienced academics working on climate and conflict through individual expert-elicited interviews and a 2-day deliberation. They concluded *'These experts agree that climate has affected organized armed conflict within countries. However, other drivers, such as low socioeconomic development and low capabilities of the state, are judged to be substantially more influential, and the mechanisms of climate–conflict linkages remain a key uncertainty. Intensifying climate change is estimated to increase future risks of conflict'* Mach *et al.* (2019).

#### 7.5.1.2 Future Risk (ID4)

In the future, these global risks, particularly associated with food and extreme weather, may become more evident and further impact on UK interests overseas (and UK supply chains) - whether in their impact on the need for military deployment (peacekeeping, or for humanitarian assistance), or local governance, tourism or impact on supply chains. In a scenario of 2°C global warming by 2100<sup>6</sup>, Harari and Ferrara (2018) estimate a 7% average increase in conflict incidence over the next 35 years (holding other variables and relationships as steady). In addition, research on the global scale since CCRA2 has highlighted the importance of indirect associations between water and conflict, such as water and energy, urban versus rural water demand, and economic impacts of floods, rather than directly assessing climate-water-conflict connections. Research on direct water conflict linkages aligns with this message of multiple contributing factors. For example, Munia *et al.* (2016) study on transboundary (shared) river basins found the frequency of cooperative or conflictive events was not directly related to increased water stress associated with upstream water use. However, Ghimire and Ferreira (2016) show that flooding events can fuel existing conflict.

While many of the direct impacts are likely to occur within particular states and lead to direct and localised conflict some impact could be felt across countries, through energy, water, and governance transmission pathways. As highlighted by Smith *et al.* (2018a) *"Water scarcity and climate-related variations in water availability can increase tensions and conflict between countries. In these and other instances, conflict was related to stress from climate-related events, but non-climatic factors also had an important role."*

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<sup>6</sup> FGOALS-g2 climate model with the RCP2.6 scenario

Motivated by the fact that urban water demand will increase by 80% by 2050, Flörke *et al.* (2018) simulated the effects of higher demand and climate change effects on shifts in timing and volume of available water on 482 of the world's largest cities. They found roughly 233 million people living in 27% of the cities considered experienced demand levels higher than surface water availability. High potential for urban and agricultural sector conflict was identified in the 19% of cities that are reliant on surface water transfers. With increasing urban poverty and inequality, the burden of this shortfall is likely to fall disproportionately on the poor.

Water can also have a more indirect impact on conflict through energy although this link is currently not strong. For example, Van Vliet *et al.* (2016) modelled the global effects of changes in water resources and electricity generation using data on 24,515 hydropower and 1,427 thermoelectric power plants, applied to climate scenarios reaching around 1.6°C and 4.3°C global warming at the end of the century<sup>7</sup>. They projected worldwide decreases in usable generating capacity of 81-86% for thermoelectric plants and 61-74% for hydropower plants for 2040-2069. This potential loss of capacity could lead to power shortages. Power shortages and blackouts have in the past led to riots and looting (Nye, 2010).

Separately, climate change, through restrictions on fuel type, hydration requirements, and changes to battlefield environments, will also drive significant changes to military deployment and strategy (Brosig *et al.*, 2019).

#### 7.5.1.3 Lock-in and Thresholds (ID4)

As highlighted by Smith *et al.* (2018a) *“Water scarcity and climate-related variations in water availability can increase tensions and conflict between countries. In these and other instances, conflict was related to stress from climate-related events, but non-climatic factors also had an important role.”* When food price shocks occur, they can lead to riots and unrest. Similarly, a FAO FPI above 140, thus providing a threshold, increased the likelihood of food riots (Natalini *et al.*, 2019).

#### 7.5.1.4 Cross-cutting and inter-dependencies (ID4)

Violent conflict arises from cascading risks between multiple interacting elements including rule of law, level of democratisation, exposure to international food prices, culture, government response, and market response. There is also strong evidence that many factors that increase the risk of civil war and other armed conflicts, such as poverty levels and income shocks, are sensitive to climate change and if these impacts are not managed, there would be an indirect effect on conflict from climate change. In addition, regions in conflict and post-conflict countries have low adaptive capacity and may themselves be highly vulnerable to future impacts of climate change.

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<sup>7</sup> The cited study used the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP) subset of 5 CMIP5 climate models. The global warming values quoted are the multi-model means for the full CMIP5 ensemble in 2081-2100 with the RCP2.6 and RCP8.5 concentration pathways. The ISIMIP subset roughly spans the full multi-model ensemble range.

#### 7.5.1.5 Implications of Net Zero (ID4)

The implications of a transition to Net Zero for the UK's exposure to climate change linked conflict risk is difficult to assess. For example, the demand for rare earth metals may increase dramatically through the transition to higher deployment of renewable technologies. If the source of these rare earth metals is within conflict-prone geographies, then the UK's exposure may increase. Ting and Seaman (2013) looked at the potential risks associated with changing demand and supplies and concluded that this may “*contribute to geopolitical tensions and instability in the East Asian region*”. However, a transition to Net Zero may also lead to a lowering of risk with a move away from dependence on more fragile oil-exporting countries.

#### 7.5.1.6 Inequalities (ID4)

Globally, the increased burden of the projected shortfall of surface water availability is likely to fall disproportionately on the poor. Within the UK, it is currently unclear how different groups may be impacted by this risk.

#### 7.5.1.7 Magnitude Score (ID4)

<b>Table 7.12</b> Magnitude score for risks to the UK from violent conflict overseas resulting from climate change					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>UK</b>	Low  (Medium confidence)	Medium  (Low confidence)	Medium  (Low confidence)	Medium  (Low confidence)	High  (Low confidence)

Climate change is recognised as an amplifier of conflict, especially within fragile states. In addition, there is increasing evidence and quantification on the exact causal pathways for conflict emerging when climate change impacts are felt. However, it mainly acts as an indirect influence within these conflicts and these conflicts have an indirect impact on the UK. Therefore, this currently represents a low risk to the UK with medium confidence (Table 7.12).

In the future climate change impacts will be larger in those fragile states and there are likely to be different risks from transitions to Net Zero as supply chains move around the world. However, as climate change is an amplifier of conflict it will only have an impact on conflict if those conflating factors, such as state fragility, exist. Therefore, this complex relationship between causal factors means that this is likely to increase to medium risk for the UK overseas interests in the future under a 2-degree pathway although with low confidence (it may be higher or lower).

## 7.5.2 Extent to which current adaptation will manage the risk (ID4)

### 7.5.2.1 Effects of current adaptation policy and commitments on current and future risks (ID4)

The UK provided £14.6 billion of Official Development Assistance in 2018, including to regions undergoing conflict, with Syria being the fifth-highest recipient country. The UK Government had a commitment to spend 50% of the Department for International Development (DfID)'s budget in fragile states every year. While a breakdown of costs of the UK's involvement in particular conflict areas is not available the total UK defence budget in 2019 was £38 billion (MOD, 2020). It is sensible to assume therefore that the UK is spending well into the millions of pounds to assist in regions affected by conflict (high magnitude, high confidence). However, we note it is not clear what the long-term development impacts on this spend will be as a result of the merger of DfID within the UK Foreign & Commonwealth Office to create FCDO, and an overall reduction in our international aid commitment in 2021, although there has already been a short term and significant reduction in UK aid-funded research.

### 7.5.2.2 Shortfall in current adaptation (ID4)

Overseas development aid is mostly reactive in conflict situations although investment in improving governance structures will reduce the underlying risk of conflict if investment is effective. It is difficult to quantify the effectiveness of this adaptation.

As noted in the CCRA2 Evidence Report, there is a potential for the UK's overseas aid budget, for example, the Conflict, Stability and Security Fund (CSSF), to cause a shift toward more short-term interventions (rapid response), as well as interventions more aligned with UK interests (ICAI, 2019), which could be at the expense of upstream prevention (SaferWorld, 2014). Current policies do not specify the optimal proportion of expenditure in long-term aid (including sustainable development and disaster risk reduction) versus humanitarian aid and the trend away from longer-term development outcomes to short-termism, including national interests rather than wider development interests, appears to be growing (Gulrajani and Calleja, 2019) and continues beyond CCRA2. There is a gap in understanding the impact on this trend in development and state fragility expenditures in exacerbating geopolitical risks.

In addition, while the Ministry of Defence includes climate change within its strategic threats' considerations (MOD, 2018; HM Government, 2015), there is a lack of evidence of a systematic review of impacts of all UK investments and partnerships across government in tackling geopolitical issues. For example, there is no systematic analysis of the UK's approach to complying with the Sendai Framework for Disaster Risk Reduction.

With climate change being an amplifier of conflict rather than a direct cause it is our view that this risk is only partially managed (with low confidence) with some worrying indications that interventions may become more short-term and less systematic.

## 7.5.2.3 Adaptation Score (ID4)

<b>Table 7.13</b> Adaptation score for risks to the UK from violent conflict overseas resulting from climate change	
<b>Are the risks going to be managed in the future?</b>	
<b>UK</b>	Partially  (Low confidence)

## 7.5.3 Benefits of further adaptation action in the next five years (ID4)

## 7.5.3.1 Indicative costs and benefits of additional adaptation (ID4)

As noted by Smith *et al.* (2018a), in the context of risks to US international assistance, “*the impacts of climate change, variability, and extreme events can slow or reverse social and economic progress in developing countries, thus undermining international aid and investments made by the United States and increasing the need for humanitarian assistance and disaster relief.*” A similar observation could be made regarding the overseas aid budget of the UK.

For mitigation of water-based conflict, more cooperative behaviour is associated with transboundary agreements (Munia *et al.*, 2016) when participating countries are governed by treaties with water allocation mechanisms that allow flexibility and specificity. Therefore, there may also be opportunities to reduce current tensions through appropriately deployed international agreements on shared resources including access to water (where rivers run between countries) or new opportunities in areas such as the Arctic.

The evidence for additional benefits from proactive engagement in reducing local tensions in regions more prone to conflict through infrastructure investment and setting up local or transboundary agreements which can underpin more cooperative behaviour between different stakeholders is increasing (for example, Munia *et al.*, 2016). The main cost associated with this is a more strategic and systems approach to investing international aid aligned to climate change adaptation associated with conflict prevention.

## 7.5.3.2 Overall Urgency Score (ID4)

<b>Table 7.14</b> Urgency score for risks to the UK from violent conflict overseas resulting from climate change (ID4)	
<b>Urgency Score</b>	More action needed
<b>Confidence</b>	Medium



The urgency score for this risk is for more action (Table 7.14). With increasing evidence of climate change acting as an amplifier of conflict since CCRA2, the impact of climate change increasing around the world, and several regions experiencing prolonged conflict and rising geopolitical tensions, the costs of inaction on adaptation is now clearer than it was in CCRA2 and therefore our view is that more action in the next five years is justified.

#### 7.5.4 Looking ahead (ID4)

The risk to the UK from international violent conflict resulting from climate change impact overseas could increase towards the longer-term. As noted above the trend of overseas development aid being increasingly used for shorter-term national (donor country) interest goals could see the undermining of longer-term development goals which would reduce the likelihood of overseas conflict.

### 7.6 Risks to international law and governance from climate change that will impact the UK (ID5)

International law provides a framework to mitigate climate risks that offers positive prospects but is highly dependent on states being willing to design ambitious climate plans and cooperate multilaterally. Climate impacts overseas have the potential to threaten and weaken international law and governance but quantifying their effects on UK's interests and values is difficult. Risks to international law and governance from climate change include human rights violations, contestation of well-established international rules, risks of sovereign defaults in emerging economies, and new legal challenges arising from low-carbon policies. Such risks have the potential to threaten the UK's economic, diplomatic and military interests and challenge its foreign policy of strengthening the rules-based international system and promoting human rights. Risks to international law and governance are amplified politically by a weakened multilateral system and states acting in their self-interest in a context of resource scarcity as well as socially by popular discontents towards globalisation. Given the systemic nature of risks to international law and governance, the UK's adaptation plan needs to be wide-ranging and include a long-term strategy to better engage with the international rule of law, its obligations and courts, in order to be seen as a credible international leader able to stabilise and influence the international system to ensure that its interests are preserved and foster prosperity and peace.

#### 7.6.1 Current and future level of risk (ID5)

##### 7.6.1.1 Current risk (ID5)

The evidence from the literature on climate risks and international law is that the international legal system is ill-adapted to respond comprehensively to the climate crisis, but no risk assessment has been carried out regarding how this situation impacts, or will impact, the UK.

At present, current risks to the UK from international law and governance principally concern climate mitigation measures. Indeed, the transition to a low-carbon economy poses significant challenges for international trade and investment rules that are not necessarily aligned with climate priorities. As a result, unresolved legal issues might frustrate the implementation of climate mitigation measures in the UK. Major uncertainties remain regarding the legality of climate-friendly energy subsidies (Espa and Marin Duran, 2018), low-carbon standards on imported goods, or carbon border adjustment mechanisms under World Trade Organisation law (Green, 2005; Condon, 2009; Veel, 2009; Espa and Marin Durán, 2018; Porterfield, 2019). This could restrain the UK's ability to design a zero-carbon import policy that could reduce the significant portion of its greenhouse gases that comes from imported goods (WWF, 2020).

Similarly, balancing the rights of foreign investors with the right of states to regulate for the public interest remains a difficult task under international investment law. The risks that international investment treaties might make governments reluctant to adopt climate mitigation policies ('regulatory chill') are heavily debated (Schill, 2007, Tienhaara, 2018). The regime is tainted with instability regarding what gives rise to an investor's legitimate expectations that a regulatory framework will remain unchanged. On the one hand, bans on fossil fuel exploration and production can be challenged by foreign investors (Di Bella, 2018) and, on the other hand, reductions in planned subsidies allocated to renewable energy projects have led to multiple arbitration cases against countries such as Spain, Italy and the Czech Republic in the past years (Faccio, 2020; Noilhac, 2020; Zannoni, 2020). Such litigation risks could affect the UK's Net Zero strategy by impacting the design of government incentive programmes in the renewable energy sector. UK investors abroad might also be affected, either positively or negatively, by rapid regulatory changes in their host countries, especially if climate and economic priorities are reviewed post-pandemic.

Direct climate impacts overseas do not currently destabilise international law and governance in such a way as to pose risks to the UK. However, a major source of concern relates to the fact that the multilateral system is currently under threat, which could amplify risks to the UK from international law and governance. It is widely acknowledged that the global order is in the process of being transformed and reshaped, as regional, non-Western, powers rise (Zakaria, 2012; Ikenberry, 2015; House of Lords Select Committee, 2018). In addition, discontent with the effects of globalisation has led to a crisis of multilateralism, perceived to be undemocratic and technocratic and unable to respond to today's global challenges. A recent wave of withdrawals from international treaties and institutions (Crawford, 2018), as well as a global backlash against human rights (OHCHR, 2018), have weakened the international legal system (Brunnée, 2018; Posner, 2017; Ulrich and Ziemele, 2019; Pellet, 2018; Brunnée and Toope, 2017). This situation raises particular concern for international climate governance that relies heavily on collective action, as evidenced when the US, under the Trump administration, announced its (now reversed) withdrawal from the Paris Agreement.

Additionally, risks to international law and governance are socially amplified by popular contestation. The perception that the transition risk to Net Zero is economically harmful, not socially supported, or historically unfair could strengthen popular discontent (Sovacool *et al.*, 2019). Conversely, the polarisation of our societies over climate action means that other segments of the population will lament the lack of ambition of international law. For instance, in recent years,

popular contestation has grown against mega-regional agreements, such as the Comprehensive Economic and Trade Agreement, perceived to be an enabler of the climate crisis (Riekmann, 2017), and could become an important obstacle for the UK's trade policy post-EU Exit.

#### 7.6.1.2 Future risk (ID5)

In the future, direct climate impacts overseas have the potential to threaten existing international rules and impact the UK's national interests and/or values. It is difficult to quantify the direct effects between a strong international legal system and the preservation and promotion of the UK's interests, but generally speaking, it can be considered that the UK benefits positively from a peaceful and stable world based on the rule of law that facilitates economic prosperity and social development.

Greater ethnic tensions, potentially driven by climate-related people movement or land degradation, may give rise to increasing violations of human rights laws worldwide. UN Special Rapporteur Alston noted in a 2019 report that climate change represents a significant threat to democracy and civil and political rights, as states might respond to climate change by 'augmenting government powers and circumscribing some rights' and as 'the uncertainty and insecurity in which many populations will be living, combined with large-scale movements of people both internally and across borders, will pose immense and unprecedented challenges to governance' (UN Human Rights Council, 2019). Such violations undermine the UK's foreign policy objective of human rights promotion and could have direct effects on the UK by resulting in climate-related increased international mobility (see ID3) and by impacting on the need for military deployment for peacekeeping purposes.

Moreover, climate risks could lead to contestation or re-interpretation of well-established international treaties that are, in their current form, inadequate to respond to climate impacts. For instance, sea-level rise could call into question well-established rules on maritime boundaries delimitation (Caron, 2014). States could be tempted to take advantage of such uncertainty, which could spark tensions between states in relation to boundary delimitation, access to natural resources, and navigation rights. Such contestations will represent direct risks to the UK's military, diplomatic, and trade interests as a major maritime power. It could have direct impacts on British Overseas Territories by aggravating tensions in territories that are disputed or by increasing pressure on their rich marine biodiversity resources.

Another example of how climate risks could weaken the existing consensus on which international treaties operate can be found in the ongoing work of the UNFCCC on 'loss and damage' that parties acknowledge does not form the basis to recognize liability or compensation rights (Decision 1/CP.21, para 51). However, if talks were to break down or result in unsatisfactory outcomes, traction might grow for compensation to the most vulnerable countries (Bodansky, 2017). As a historical emitter, the UK could face risks of disputes that would represent a reputational risk for the country.

In addition, evidence is emerging that climate impacts pose a systemic risk to national economies due to the immediate and longer-term shocks of climate-related events and public spending for reconstruction (Mrsnik *et al.*, 2015) and could potentially increase the risk of sovereign defaults in emerging economies (Cevik and Jalles, 2020; Mallucci, 2020). This could have significant implications

for the UK, financially because the UK is a significant investor and potentially geopolitically in case of regional destabilisation around the failed state.

An important pathway of transmission of international climate risks and impacts to the UK is through states acting in their narrow self-interest, which could have a destabilising effect on international peace and international trade routes. This could, in turn, undermine the UK's economic interests and make its commitment to protecting the rule of law, democracy, and human rights worldwide more difficult to implement. The CCRA2 Evidence Report Chapter 7 warned that increased tensions on resources, exacerbated by climate change, 'could lead to an increase of state-led enterprise, resource protectionism and strategic bilateral agreements that secure long-term access to resources at the expense of the global markets upon which UK businesses rely' (Challinor *et al.*, 2016; p.46) – and this observation remains valid. Pressures from competition over scarce resources or climate migrations are likely to drive political tensions internationally and lead to the further rise of inward-looking nationalism and populism. The impacts of climate change could be far-reaching for transboundary water resources, in particular in some of the world's most important drainage basins, such as the Rhine, Danube, Mekong, Nile, or Indus. Risks to international water law identified in the CCRA2 Evidence Report on the basis that freshwater resources are likely to be scarcer remain high. Indeed, while international water law and institutions offer reliable foundations to ensure that international watercourses are used in a fair, equitable, and sustainable manner (Vinca *et al.*, 2020), climate change impacts could result in tensions between neighbouring states (Cooley and Gleick, 2011; Jafroudi, 2018). Similarly, as demand for fish stocks and minerals rises, pressure on the Antarctic Treaty and its protocols that regulate international relations on the continent and support scientific activities as well as environmental protection could increase (Nature, 2018; Patrick, 2019). Risks arising from resource scarcity could also be socially amplified: for instance, as fishing stocks migrate and diminish, international fisheries agreements, such as EU Fisheries Partnership Agreements with developing states, might become contested and could impact both the UK's fisheries partnerships for food security and prices (Brandt and Kronbak, 2010; Mendenhall *et al.*, 2020).

#### 7.6.1.3 Lock-in and thresholds (ID5)

Reputational risks are important in relation to this risk, and therefore a long-term perspective is needed to mitigate them. COP 26 is an opportunity to lock in positive international collaborations and partially mitigate future risks.

#### 7.6 1.4 Cross cutting risks and Inter-dependencies (ID5)

This risk is closely intertwined with other risks presented here, including ID3 on international human mobility, ID4 on violent conflict overseas, and ID6/7 on international trade routes. International law and governance offers means of mitigating some aspects of these risks and there are therefore co-benefits for ID5 in the management of these other risks.

### 7.6.1.5 Implications for Net Zero (ID5)

The current lack of legal clarity regarding the compatibility of climate measures and trade and investment rules could have detrimental impacts on the UK's Net Zero strategy, in particular, if the legality of certain policy levers, such as those seeking to address carbon leakage or aiming to attract foreign green investors, were to be challenged. The UK's Net Zero strategy might need to be brought in line with any future legal clarifications or developments to ensure that the design of climate mitigation policies measures is consistent with international obligations.

### 7.6.1.6 Inequalities (ID5)

It is currently unclear how different groups may be impacted by this risk.

### 7.6.1.7 Magnitude Score (ID5)

<b>Table 7.15</b> Magnitude score for risks to international law and governance from climate change that will impact the UK (ID5)					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
UK	Low  (Medium confidence)	Medium  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)

All in all, at present, the impacts of climate risks on international law have had limited economic or social consequences for the UK. However, in the long-term, they are likely to grow, in particular if political and social contestation grows and if states are unable to cooperate to develop adequate international legal frameworks. Quantifying the economic impacts of disruptions to the international rule of law is extremely difficult because the consequences can vary significantly in terms of nature and magnitude and risks are transmitted in a non-linear manner across multiple impacts. A destabilised world order, where, for instance, tensions over natural resources are high and navigational rights disputed, could potentially cost the UK in the order of £ hundreds of millions in damages or foregone opportunities per year. An increase in global temperatures and/or a delay in meeting these temperature objectives is likely to increase the magnitude of the impacts because it could further destabilise international relations; however, it is not necessary because it is also dependent on a combination of other, non-climate related factors. There is, therefore, low confidence in future magnitude scores. Indeed, the international legal system is very reliant on changing political circumstances that make predicting the future level of risk difficult. The extent to which climate risks and their transmission pathways will be attenuated depends on the willingness

of governments to cooperate internationally and the ability of existing international rules and institutions to diffuse any possible tensions.

## 7.6.2 Extent to which current adaptation will manage the risk (ID5)

### 7.6.2.1 Effect of current adaptation policy and commitments on current and future risk (ID5)

The international legal system, as noted in the CCRA2 Evidence Report, offers significant opportunities to address the drivers of risks arising from climate change, inter alia thanks to the Paris Agreement and the UN Sustainable Development Goals, both adopted in 2015 and considered to represent a transformative roadmap towards a more sustainable world for the decades to come. It is, however, widely acknowledged that these regimes have inherent limitations because their bottom-up approach leaves implementation to the discretion of states with little international oversight (Bodansky, 2016). The UK has the potential as a climate leader to influence the international climate regime and hence limit global climate risks in the first place. Indeed, the UK is widely recognised to be a climate leader, ambitious domestically – the 2008 Climate Change Act is largely considered to be a landmark piece of climate legislation that is used as a model worldwide (Norton, 2018) – and internationally – it was under the UK’s Presidency that the UN Security Council discussed for the first time the interlinkages between climate change and international peace and security in 2007 (United Nations Security Council, 2007). The UK considers tackling climate change and biodiversity loss to be its ‘number one international priority’ (HM Government, 2021). COP 26, co-organised and hosted by the UK, is an opportunity to lead on the design of new international collaborative initiatives, such as the public-private Coalition for climate-resilient investment, a COP 26 flagship initiative set up in 2019. The legacy of the COP, either positive or negative, is likely to have a significant impact on the reputation of the UK in the environmental field in the medium-term future. In this context, domestic delivery on environmental issues including climate change adaptation, which has lagged in progress (CCC, 2019) will be critical to reinforce the UK’s credibility and legitimacy as an environmental leader and to showcase the UK’s leadership.

### 7.6.2.2 Shortfall in current adaptation (ID5)

Given the systemic nature of risks to international law and governance, the UK’s adaptation plan for this risk needs to be wide-ranging and cannot cover only climate-specific diplomacy. Indeed, our expert opinion is that the UK’s diplomatic action outside of the climate realm could significantly impact its ability to attenuate risks to international law and governance from climate change. In this context, our view is that perceptions that the UK’s influence on the international scene has diminished in recent years need to be addressed. Its withdrawal from the European Union has been interpreted to symbolise a wider retreat from multilateral cooperation and the UK risks becoming isolated internationally without the same level of support from its European partners (House of Commons Foreign Affairs Committee 2017). In addition, the UN Security Council, where the UK holds a permanent seat, has lost its credibility as it has become paralysed in the context of disagreements between P5 members in relation inter alia to Syria (Butchard, 2020). Conversely, the UN General Assembly, where the UK lacks support and has suffered unexpected defeats in the past few years (e.g., in relation to the *Chagos* advisory opinion and the International Court of Justice (ICJ) election, both discussed below), is becoming more assertive (UK Government, 2018).

It is arguable that the image of the UK as an international law champion has in recent years been eroded (e.g., Philippe Sands in *The Times*, 2020). The Government's admission in September 2020, in the context of EU Exit, that passing the Internal Market Bill would 'break international law' if enacted (House of Commons, 2020) received significant media coverage worldwide. Another source of concern has been the UK's rejection of the conclusions of the ICJ's advisory opinion on the *Legal Consequences of the Separation of the Chagos Archipelago from Mauritius in 1965*, published in February 2019 (followed by a UN General Assembly vote in November 2019), calling upon the UK to 'bring an end to its administration of the Chagos Archipelago as rapidly as possible' (International Court of Justice, 2019). Maintaining the UK's reputation as an upholder of international law is important in the context of climate change to ensure that the UK remains a credible voice when defending a rules-based international order, in the event, for instance, that states would start disputing established law of the sea rights and duties.

The UK's relative disengagement with the ICJ, the principal judicial organ of the United Nations, accelerated by the fact that it unexpectedly lost its judge in the 2017 elections - a first for a permanent member of the UN Security Council (House of Commons, 2018) - is potentially problematic because international dispute settlement is likely to play an increasingly important role in the context of climate change (Verheyen and Zengerling, 2016). On the one hand, inter-state tensions between those most responsible for climate change and those most affected might increase and the UK, as a historical emitter, needs to ensure that it is best positioned to respond legally to such disputes; on the other hand, the UK should also preserve its rights to bring international claims against other states in breach of their international climate commitments.

#### 7.6.2.3 Adaptation Score (ID5)

<b>Table 7.16</b> Adaptation score for risk to international law and governance from climate change that will impact the UK	
<b>Are the risks going to be managed in the future?</b>	
<b>UK</b>	Partially  (Medium confidence)

The risk is only partially managed (medium confidence). The UK is a proactive leader in the field of international climate change governance and this role is likely to be strengthened as it hosts COP 26 towards the end of 2021. However, our view is that further action will be needed to overcome any reputational risks associated with a perceived disengagement of the country with multilateralism and international law.

## 7.6.3 Benefits of further adaptation action in the next five years (ID5)

### 7.6.3.1 Indicative costs and benefits of additional adaptation (ID5)

Diplomacy is the main means of adaptation in relation to this risk. Further engagement with multilateral processes and institutions would have benefits for ensuring that the UK preserves its interests and strengthens its image as a respected multilateral player. This could include engaging constructively with a multiplicity of processes and initiatives in the context of climate change, such as inter alia by supporting the work of the International Law Commission on sea-level rise in relation to international law started in 2019, the work of the UNFCCC on loss and damage (including its Task Force on Displacement) and the on-going modernisation of the Energy Charter Treaty. There would also be benefits from producing a clear plan to meet the challenges posed by a shift in UK relationships with traditional allies and changing dynamics at the UN, to coordinate its activities with the EU, and to build new partnerships with inter alia the Commonwealth. Whilst the short-term benefit of these adaptations is small, it rises on longer timescales, commensurate with the increase in risk magnitude. Planning is needed now in order to enable adaptation in the future.

### 7.6.3.2 Overall Urgency Score (ID5)

<b>Table 7.17</b> Urgency score for risks to international law and governance from climate change that will impact the UK	
<b>Urgency Score</b>	More action needed
<b>Confidence</b>	Medium

The urgency score for this risk is for more action needed (Table 7.17). This score has been given because the evidence reviewed above suggests that while current risks have been identified as low, they are likely to rise in the future and their successful mitigation depends on factors that require constant engagement and long-term planning. These include building the UK's reputation as a supporter of a strong international order, ensuring the stability and resilience of the international legal system, and negotiating the adoption of new international rules protecting the UK's interests.

Evidence for the urgency of dealing with this risk has increased since CCRA2 had identified international law and governance as an area for further investigation. The change in assessment between CCRA2 and CCRA3 is not directly climate-related: assessment of the underlying climate risks has not changed significantly since CCRA2, but the changes in ongoing actions that support adaptation, as outlined above, leave a more significant adaptation gap in our view. Given the opportunities associated with building new foundations for the UK's engagement with the international order post-Brexit and with strengthening international partnerships post-COP 26, the next five years offer a window of opportunity to reduce this adaptation gap.



#### 7.6.4 Looking ahead (ID5)

It is at present difficult to quantify the exact implications for the UK of the impacts of climate risks on international law and governance because they are highly dependent on a complex combination of factors. However, the literature is clear that international law is weakened by the climate crisis as it struggles to respond to a challenge that questions some of its foundational concepts, such as that of statehood or territory. Given that international peace and security is dependent upon a well-established international legal system, risks of disillusionment and push back against the multilateral system are concerning. It is certain that engagement with international law needs to follow a long-term strategy in order to build the trust and credibility needed when the international legal system is destabilised and threatens the UK's interests and values. Such a strategy is important to build trust and the legitimacy of 'global Britain'.

### 7.7 Opportunities from climate change (including Arctic sea ice melt) for international trade routes (ID6)

The opportunities from climate change to extend international trade routes are currently limited to potential benefits from increased access to the Arctic and provision of maritime services. However, associated risks, some military in nature, coupled with the small magnitude of opportunity, lead to a current magnitude designation of Low (High confidence). Longer-term, as warming continues, this rises to High (Low confidence). There is no clear need for action in the next five years on this issue, since:

- i. The opportunities relating to sea passages opening up are being closely monitored by a range of commercial operators in maritime shipping and ancillary industries.
- ii. The UK Government is also involved in International Maritime Organisation activities related to the regulation of potential activities.

#### 7.7.1 Current and future level opportunity (ID6)

##### 7.7.1.1 Current Opportunity (ID6)

CCRA2 identified that as a result of melting sea ice the opening of Arctic trade routes presents an opportunity for increased trade (Challinor *et al.*, 2016). The present analysis confirms that the UK has some capacity to benefit from increased access to the Arctic as a consequence of climate change. It could still benefit from increased tourism and the provision of maritime services in addition to trade.

Northern Sea Route (NSR) traffic has continued to grow since 2016 and is increasingly year-round. Russian officials claim that the arrival of new icebreakers will mean year-round navigation will be possible in the 2020s (Sevastyanov and Kravchuk, 2020). The principal driver is the massive development of Liquefied Natural Gas (LNG) projects in the Russian Arctic, originally in terms of the delivery of construction materials and supplies, and latterly through the export of Arctic LNG to

Europe (including Thamesport in the UK) and Asia. These LNG projects have proceeded ahead of schedule. The evacuation of coal from the Russian Arctic is also a driver of increased trade volumes along the NSR. The Russian government is continuing to invest in developing the route (Didenko and Cherenkov, 2018), with President Putin decreeing in 2018 that traffic should expand to 80 million tons by 2024 (previously not envisaged before 2030). Russia is committed to developing the NSR. However, state support potentially distorts the commercial benefits/risks, and it is unclear whether similar growth could be envisaged without extensive investment from the Russian government.

In terms of transit shipping, China's state-owned COSCO is leading interest. It has continued to transit Arctic routes every year since 2013, with a record 14 transits of the NSR planned for 2019 (CHNL Information Office, 2019). COSCO has previously used the route to deliver wind turbine equipment and parts to the UK. In 2018, the Chinese government further announced its intention to work with Arctic partners to jointly build a 'Polar Silk Road' through 'developing Arctic shipping routes', suggesting that there will continue to be state backing for COSCO to actively develop viable commercial routes through the Arctic (The State Council of the People's Republic of China, 2018). Danish-shipper Maersk sent the first-ever container ship through the NSR in 2018. The ship, capable of carrying nearly 3,600 containers, was part of a new fleet of seven ice class 1A feeder container ships designed to operate in the Baltic Sea. Nevertheless, it experienced many challenges, having to deviate from its planned route and required assistance from a Russian nuclear icebreaker. In 2019, Maersk announced that it was now working with Russia's nuclear icebreaker operator Atomflot to explore the possibility of offering a joint seasonal service to meet the demand for transport between the Far East and West Russia. Meanwhile, other major ship operators (Teekay, MOL) have also started to gain experience operating along the NSR after assisting with LNG shipments. While transit numbers remain very low compared to Suez/Panama, the likelihood of a market emerging for specialized and ad-hoc container shipping is increasing. Several other shippers have said they will not use the route (Seatrade Maritime News, 2020).

In 2016, the IMO adopted the Polar Code, which subsequently came into force in 2017. The Polar Code makes mandatory requirements relating to the operation of ships in polar waters, that include strict regulations around ship design, construction, and equipment; operational and training concerns; search and rescue; and the protection of the environment and ecosystems of the polar regions (IMO, 2017). Meanwhile, the IMO is also continuing efforts- that began in 2011- towards banning Heavy Fuel Oil in the Arctic in the 2020s. HFO is the most consumed marine fuel in the region. Russia which has not yet agreed to the ban has signalled it might be willing to transition to LNG-powered vessels and is already operating the first of four large capacity LNG-powered oil carriers. Switching from HFO to lighter fuels such as LNG is likely to slow the development of Arctic shipping so a ban in the 2020s could further delay the maritime development of the Arctic.

The passage of the Crystal Serenity through the Northwest Passage in 2016 attracted much international interest as a tourist venture. The luxury cruise liner with over 1,000 people aboard completed the voyage in 32 days. A second voyage was undertaken in 2017. However, Crystal cruises have since announced they are unlikely to do so again with a large cruise ship (the company has recently invested in a small polar-class mega-yacht). The voyages through the NWP attracted significant criticism from environmentalists and local communities owing to the environmental risks

generated; and poor emergency response and rescue capabilities present a risk to those undertaking the voyage (Qian *et al.*, 2020).

#### 7.7.1.2 Future Opportunity (ID6)

The construction and launch of the RSS Sir David Attenborough is a notable success story for the UK maritime sector. The Attenborough is arguably the most significant ship to be built in the UK for several decades and provided an example of best practice in terms of how multiple UK-based firms can work together to deliver a world-class build. The UK maritime sector (including the maritime service sector in the City of London) is now well-placed to use the expertise it has developed to advise on and lead the rest of the world on how to implement the Polar Code into new build designs. It has also restored its own capacity to build world-leading, cutting-edge, ice-capable ships. The success of the Sir David Attenborough signals that there is potential across the UK maritime sector (design, construction, services) to take advantage of growing demand for ice-capable ships to ply emerging Arctic trade routes.

Growing commercial interest in Arctic trade routes also brings with it growing interest in military opportunities and risks. For example, The US is in the process of strengthening its commitment to securing emerging 'strategic corridors' in the Arctic (Department of Defence, 2019), which are expected to enable the flow of forces globally as access increases. Meanwhile, in 2018, the UK Ministry of Defence announced that it would put 'the Arctic and High North central to the security of the United Kingdom' through the development of a new defence strategy for the region, although this has yet to be published (Depledge *et al.*, 2019). The military requirement to improve situational awareness in the region will increase demand for innovation and ultimately cheaper technological solutions, which could create commercial opportunities for the UK. The potential for a greater deployment into Arctic regions has implications for the equipment and training needs of the UK's military (IMCCS, 2020).

There is an awareness, particularly in the Scottish Highlands and Islands of the potential for port development to serve opportunities relating to sea passages opening up. There is reference to the North East Passage and Scotland's strategic location in this regard in Scottish Government (2014) National Planning Framework 3 (p27 and 54). This issue may present opportunities for Northern Ireland as well.

#### 7.7.1.3 Lock-in and thresholds (ID6)

The uncertain pace of sea routes opening – both in any given year, but more generally over longer time periods - may result in sunken assets through the premature investment of ships designed for arctic voyages, as well as premature investment in port development to serve Arctic shipping. The loss of summer ice is a threshold effect that gives rise to the opportunity documented here.

#### 7.7.1.4 Cross-cutting risks and inter-dependencies (ID6)

Increased shipping from the north links partially to Risk N16: Risks to marine species and habitats from pests, pathogens and invasive species' (Chapter 3: Berry and Brown, 2021) as more Arctic travel may lead to risks in the UK's waters.

### 7.7.1.5 Implications for Net Zero (ID6)

The implications for Net Zero related to this risk are unclear.

### 7.7.1.6 Inequalities (ID6)

It is currently unclear how different groups may be impacted by this risk.

### 7.7.1.7 Magnitude Score (ID6)

<b>Table 7.18</b> Magnitude scores for opportunities from climate change (including Arctic ice melt) on international trade routes					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>UK</b>	Low  (High confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)	High  (Low confidence)

The small number of opportunities identified above, coupled with the associated risks, lead to a current magnitude designation of Low (High confidence). Longer-term, as warming continues, this rises to High (Low confidence). The low confidence arises from the geopolitical and social issues that may constrain, or allow, opportunities to be realised.

## 7.7.2 Extent to which current adaptation will manage the risk (ID6)

### 7.7.2.1 Effects of current adaptation policy and commitments on current and future risks (ID6)

The opportunities relating to sea passages opening up are being closely monitored – and where appropriate, acted on - by a range of commercial operators in maritime shipping and ancillary industries. The UK Government is also involved in International Maritime Organisation (IMO) activities related to the regulation of potential activities.

### 7.7.2.2 Shortfall in current adaptation (ID6)

Our view is that current adaptation measures are sufficient to manage this opportunity. The CCRA2 Evidence Report identified that as a result of melting sea ice, the opening of Arctic trade routes presents an opportunity for increased trade. The present analysis confirms that the UK has some

capacity to benefit from increased access to the Arctic as a consequence of climate change and that actions are taking place to consider this.

The UK could still also benefit from increased tourism and the provision of maritime services. As noted above, the UK maritime sector has also demonstrated that it can design and build a world-class, ice-capable ship (the RSS Sir David Attenborough) that meets the latest regulatory requirements. However, as noted above, there are safety and environmental risks involved, and so insurers and underwriters remain cautious about providing services to Arctic shipping.

### 7.7.2.3 Adaptation Score (ID6)

<b>Table 7.19</b> Adaptation score for opportunities from climate change (including Arctic ice melt) on international trade routes	
<b>Are the opportunities going to be managed in the future?</b>	
<b>UK</b>	Yes  (High confidence)

## 7.7.3 Benefits of further adaptation action in the next five years (ID6)

### 7.7.3.1 Indicative costs and benefits of additional adaptation (ID6)

There is some projected analysis (e.g., Bekkers *et al.*, 2016) which indicates that opportunities from climate change (including Arctic ice melt) on international trade routes could be large including from the economic effects of trade that is facilitated by a reduction in transport distance between suppliers and consumers. The effect on UK GDP was estimated to be equivalent to an annual increase of 0.24%, although this was associated with year-round (not just summer) transport access. There are also potential tourism opportunities that increased access to the Arctic allows, and associated port development in locations that facilitate these trade and tourism opportunities. While these would need to be seen against potentially very large negative impacts from an ice-free Arctic for other reasons (e.g., loss of or damage to arctic ecosystems, potential higher global warming levels, impacts on European weather, etc.) they do indicate potential economic benefits. There is an issue whether these benefits will be fully realised by non-government adaptation alone, and it is likely that higher benefits could be achieved for the UK (as compared to competitor coastal countries) through some enabling actions from government, which would have likely low costs.

## 7.7.3.2 Overall Urgency Score (ID6)

<b>Table 7.20</b> Urgency score for opportunities from climate change (including Arctic ice melt) on international trade routes	
<b>Urgency Score</b>	Watching brief
<b>Confidence</b>	Medium

The urgency score for this risk is a watching brief (Table 7.20). The opportunities relating to sea passages opening up are being closely monitored by a range of commercial operators in maritime shipping and ancillary industries. The UK Government is also involved in International Maritime Organisation activities related to the regulation of potential activities. There is also awareness, particularly in the Scottish Highlands and Islands of the potential for port development to serve these activities. This issue may present opportunities for Northern Ireland as well in terms of the growing importance of its ports.

## 7.7.4 Looking ahead (ID6)

As the Arctic becomes increasingly ice-free, the potential for significant routing of trade – and the opportunities for the UK – becomes more likely. However, the scale of the benefits clearly depends on many unpredictable factors, including the possibility of deglobalisation vs further liberalisation of trade.

## 7.8 Risks associated with international trade routes (ID7)

ID1 covers risks to the food supply from climate-related events overseas. Whilst the focus of that risk is on food, where the impact of weather on production is notorious, ID7 covers all traded goods. Climate-related disruption to non-food supply chains may occur in production facilities (e.g., floods affecting factories or mines), but perhaps is more likely to impact supply-chain logistics, which can be interrupted in multiple ways. COVID-19, for example, disrupted supply chains through the closure of centralised processing facilities, the cessation of transport flows due to grounding of vehicles, lack of labour, and delays at borders. With globalised supply chains characterised by ‘just-in-time’ delivery, high efficiency but low redundancy, they can be fragile and lack resilience to disruptions. Given the projected (and observed) increase in disruptive events, this risk may become more potent in future, warranting further investigation.

According to UNCTAD (2018), global trade in goods in 2017 was over \$17tn, having increased by a factor of about 1.7 over the decade. Trade in essential supplies, like food, is a small proportion of this. According to Ercsey-Ravasz *et al.* (2012), in 2008 over \$1tn of food was traded globally.

Teleconnections through global markets – the trade in goods, and its finance - can increase or decrease risk. When shocks are small, stocks are large, where there is a diversity of supply geographically, and transparency is high, trade can act to create spatial buffering and thus absorb the shocks. However, when shocks are large, and concentrated in regions that dominate the export

markets (e.g., US dominates the maize market), and with just-in-time supply chains, the global system becomes fragile (Puma *et al.*, 2015), and risk can be amplified when other exporting regions respond to production shock with restrictive export policy responses (d'Amour *et al.*, 2016). Losses due to disasters can spread to other sectors, causing additional indirect loss that can represent a significant, and sometimes dominant, share of total loss (Acemoglu *et al.*, 2012). However, the understanding of “ripple effects” is not strong: impact cost models tend to underestimate costs of climate extremes, and they cannot resolve all economic loss along a complex supply chain (Otto *et al.*, 2017).

Climate hazards can interrupt supply chains in a multitude of ways: on production (agriculture, extractive industries, manufacturing), on transport and logistics, on labour supply, on retail and its logistics, and on-demand. These direct impacts can interact with a range of other factors that amplify (or buffer) impacts, as outlined in CCRA2 (Challinor *et al.*, 2016). For example, with just-in-time supply chains (particularly for perishable produce) political events (such as trade wars, EU Exit) can potentially increase the magnitude of, or perception of the magnitude of, any climate-induced shortfall, leading to an amplifying risk cascade (see also ID10).

Furthermore, impacts can be extensive in the temporal domain and lead to a whole series of knock-on effects. For example, whilst not due to a climate impact, the 2018-2019 US-China trade disruption arose from the US protecting its manufacturing industries. This led to China levying tariffs on US agricultural imports, leading to significant cuts in US exports (Li *et al.*, 2020; Inoue and Todo, 2019). This in turn led to new opportunities for agricultural expansion as other countries strove to fill the gap. This may have played a part in incentivising Brazil's expansion into forests (Fuchs *et al.*, 2019), exacerbating climate change through emissions associated with land conversion, and thus increasing climate hazards which will impact further on supply chain risks.

## 7.8.1 Current and future level of risk (ID7)

### 7.8.1.1 Current Risk (ID7)

Risks to food trade are highlighted in ID1, and; they are primarily couched around climate-change related production shocks and market responses. There is, as has been illustrated by COVID-19, the potential for much wider disruption in supply chains coming into the UK from overseas, not simply associated with the impacts of weather on production. These risks are more articulated around supply-chain logistics and the potential for transport to be affected. Such impacts are various and include impacts on inland logistics (e.g., extreme heat buckling railway tracks for key routes; drought affecting river levels, e.g., in the Mississippi transport network; or storm damage to key ports of transport routes). COVID-19 gives insight into the resilience of supply chains following major disruption (arising from lack of labour for transport, lack of airfreight, or border closures). However, its impacts are largely not yet in the literature on which to draw conclusions.

Trade is also not simply a matter of a country producing a product and exporting it to a country that uses it. For many commodities, perhaps especially food and electronic/automotive consumer goods, products are themselves manufactured from multiple supply chains before being sold. A feature of modern economies is therefore the reliance on long, complex, multinational supply chains (Cepeda-

López *et al.*, 2019). Increasing efficiency means supply chains are lean: with few local stocks being held, rather the expectation of just-in-time deliveries of goods. This increasingly leads to a systematic fragility (Puma *et al.*, 2015) and therefore systematic risk. For example, the impacts of the Fukushima disaster were felt globally due to the constriction of components for other products manufactured in Japan, and the early-felt global issues arising from COVID-19's China lockdown included a restriction on the flow of many products originating from China (such as medical supplies and PPE – personal protective equipment for the medical profession).

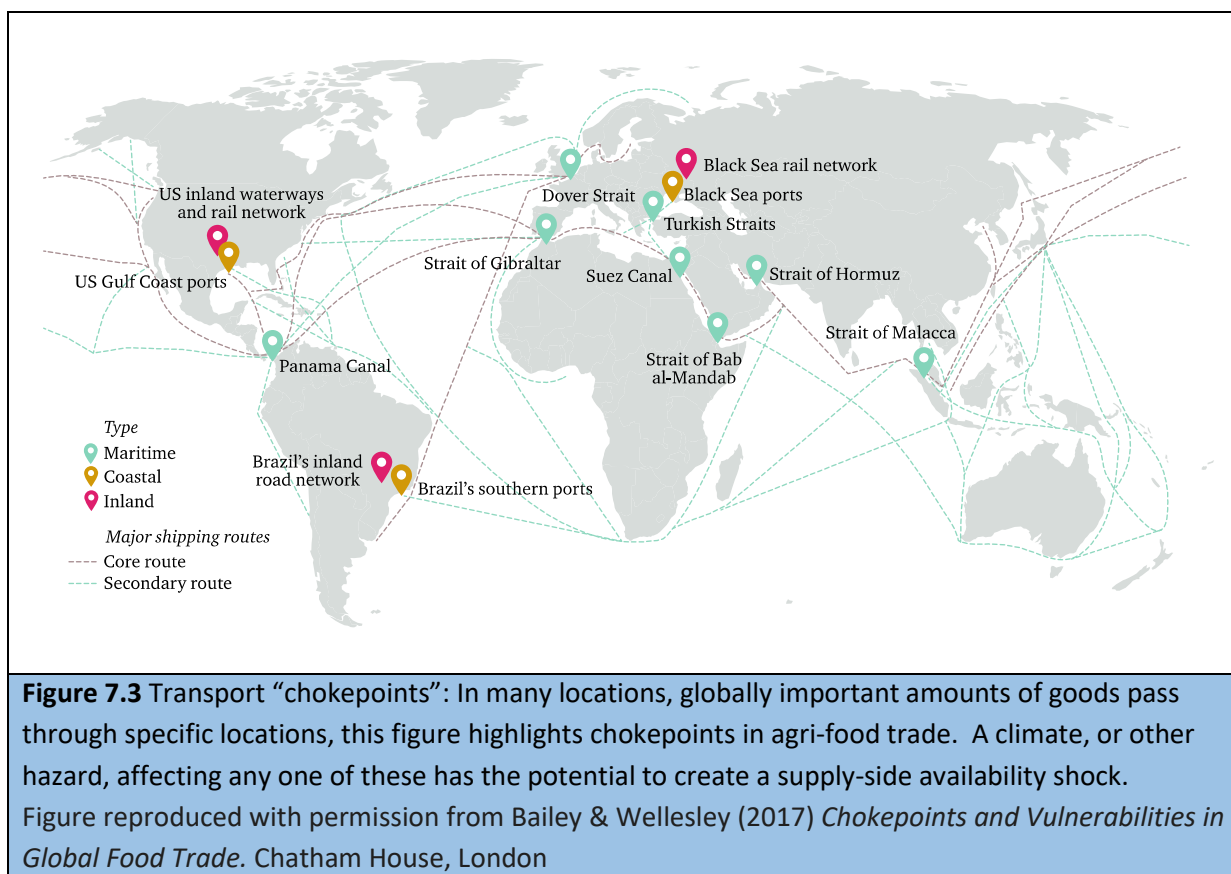
#### Box 7.3 Case Study Thailand Floods

Flooding in Thailand in 2011 had a severe cost to human life, infrastructure and the global supply chain, particularly the movement of goods and market transmission pathway. The magnitude of the flooding resulted from the co-occurrence of multiple anomalous events, and was attributed to human induced climate change, with an increasing probability of occurrence of an event of the same magnitude under future climate change (Promchote *et al.*, 2016). The floods in Thailand in 2011 provide a case study example of impact chains in the electronics industry following a low likelihood high impact flooding event internationally, identifying several vulnerabilities within the current production and distribution system, and risks transmitted to the UK. Affected supply chains included car manufacture (Honda Co, Toyota Motor Co), computer manufacture (Lenovo Group Ltd, Samsung Electronics, ACER Inc), impacting availability and prices of parts e.g., hard drives, DRAM chips, and products (Ploy Ten and Chang-Ran, 2011).

The market price of computers experienced a sharp spike in October 2011, and remained high into 2012, and sales losses were reported by a large range of producers following the period, due to the increased price of component parts, including Garner, Sony, Sharp, Panasonic, Intel, Nvidia, and AMD. The electronics and motor vehicle economies of Japan were severely affected, for example the transport industry production was estimated as 84.0% less in June 2012 than June 2011 before the floods, and some affected industrial estates reported up to 14% business closure by June 2012 (Haraguchi and Lall, 2015). Some international companies reported share losses in response to the floods, for example 5% decrease by Dell and a 12% decrease by UK company Pace (Makan and Simon, 2011).

International supply chains are most typically routed by sea, where the costs of bulk transport are minimised (see Figure 7.3). Work by Chatham House (Wellesley *et al.*, 2017) illustrates that trade routes, whose infrastructure is crucial to global functioning, get funnelled through a small number of globally important “chokepoints”, whose interdiction could have a crucial impact on global supply. These include many routes that are associated with areas of broad geopolitically instability (e.g., the Straits of Hormuz, Red sea routes, including Suez), which may also be destabilised by climate impacts on those nations (e.g., areas of conflict exacerbated by climate change – see Risks ID3, ID4, and ID10). The world's busiest port, Shanghai, handles over 40m TEU (‘twenty foot-equivalent units’), and more than 25% of all China's trade flows through the port, yet flooding – in 2020 areas of the port were closed due to the severe floods on the Yangtze - and sea-level rise is of growing threats to its functionality.





Other chokepoints are areas where there are direct climate risks to the area and its infrastructure (e.g., hurricane risk in the US’s Gulf of Mexico ports, Hurricane Katrina in 2005 created damage of ~\$100m on Mississippi’s ports, and a loss of revenue of ~70%) (The Joint Committee on Performance Evaluation and Expenditure Review, 2006). In addition, 60% of US grain trade is funnelled down the Mississippi to these ports, via barges, and low levels of flow (associated with drying conditions) has the further potential to limit trade flows.

As discussed in CCRA2 the potential for a squeeze on supplies to have an amplified price effect due to panic buying on markets, coupled with policy decisions that put national interests above market interests. In *extremis*, a relatively small effect on supply may amplify into a large effect on price/availability through these mechanisms (Challinor *et al.*, 2016).

#### 7.8.1.2 Future Risk (ID7)

Our view is that recognition of the potential supply chain risks has risen in the last few years, with planning for supply chain disruption due to EU Exit on the one hand and managing supply chains during the COVID-19 pandemic on the other. Such events are expected to become more common due to a growing incidence of extreme weather (Chapter 1: Slingo, 2021) globally. Whilst recognition of these issues is becoming greater, each disruptive event has in the past been treated as exceptional (see discussion below in ID10). There remains some under-recognition that such events are likely to become more prevalent. Hence, there is scope for more action to build resilience into the ‘normal functioning’ of supply chains to mitigate the impact of such events. The extent to which the market is incentivised to do this alone is uncertain at the time of writing.

Beyond the generic impact of climate change on trade, ID6 highlights opportunities that occur with the opening up of the Northern Sea Routes with Arctic melting. Although commercial activity remains limited, interest in potential trade routes is producing a degree of geopolitical risk that may be exacerbated in the future. Russia has tightened the rules it applies to users of the NSR and some fear it is pushing for de facto control of all shipping through the NSR and adjacent Arctic waters (Moe, 2020). Russia is also building/upgrading a network of military bases along the NSR (Boulègue, 2019). The United States has responded in turn by threatening to conduct Freedom of Navigation Operations through Russian and Canadian Arctic waters (The Wall Street Journal, 2019). In May 2020, UK and US warships approached Russian Arctic waters for the first time since the Cold War. In September 2020, they did so again (along with Norwegian and Danish forces), to signal their determination to uphold freedom of navigation above the Arctic Circle (Royal Navy, 2020) in the face of Russian attempts to tighten its legal and military control of the region. More generally, increased military exercise activity and missile-testing have the potential to cause disruption to maritime activity by forcing sea traffic to divert. The potential for further nuclearization of Russian naval forces to assist with Arctic maritime operations also presents challenges (Goodman and Kertysova 2020). Another risk is that rising great power competition will undermine trust and lead to increased suspicion that maritime surveillance and commercial operations along Arctic trade routes are a front for military interests, raising the potential for unintended armed conflict. Washington has already warned that expanding Chinese commercial activity could pave the way for a permanent Chinese security presence in the region longer-term (United States Department of State, 2019). Meanwhile, several NATO countries including the UK are increasingly mindful of the potential for Russia to use military assets stationed in Arctic bases to threaten maritime security and sea lines of communication in the North Atlantic.

#### 7.8.1.3 Lock-in and thresholds (ID7)

As per ID1, post-EU-Exit trade deals may potentially create lock-ins through the reliance on imports from countries and trade-routes that are more prone to climate disruption than current trade (i.e., the significant volumes from Europe via the Channel Tunnel, replaced with imports from the North Atlantic region and Australasia).

#### 7.8.1.4 Cross-cutting risks and Inter-dependencies (ID7)

As per ID1, there are significant inter-dependencies in the way that trade may respond to climate hazards and the context (geopolitical, policy, market, social) within which the hazard occurs. For example, co-incident hazards are more likely to amplify disruptions to trade networks; or climate hazards occurring when the trading system is under other pressures (from conflicts, or trade-wars).

#### 7.8.1.5 Implications for Net Zero (ID7)

Net-zero commitments around the world may have some influence on trade-volumes through impacts to reduce emissions in transport modes such as shipping. In addition, low carbon energy systems are likely to be less trade intensive than fossil fuels and impact on trade-volumes (coal, oil, LPG). This reduction in trade intensity of the energy sector would likely loosen the bonds (and

tensions) that bind some countries together. In the very long-term, low-cost sustainable energy will likely reduce one of the key sources of conflict and drivers of geopolitical tension in the world, but in the shorter-term, the transition creates risks to manage and new threats to mitigate. In addition, the development of cleaner technologies will both change trade-flows and also the strategic importance of minerals (for example, oil decreases in importance and cobalt – for PV – becomes more important).

Furthermore, a focus of net-zero planning is often to increase efficiency (therefore removing functional redundancy) and reducing resilience. Recognising this trade-off is important for managing this risk (and others: ID1, ID10).

#### 7.8.1.6 Inequalities (ID7)

As per ID1, inequalities are exacerbated by trade-related disruptions, as they are associated with changing prices and availability, for which low-income households may be most exposed. As per ID2, opportunities (from climate change induced changes in production and trade) may, under some circumstances lead to lower consumer prices. Lower prices may be positive or negative for low-income households.

#### 7.8.1.7 Magnitude Scores (ID7)

<b>Table 7.21</b> Magnitude score for risks associated with international trade routes					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>UK</b>	Medium  (Low confidence)	Medium  (Low confidence)	High  (Low confidence)	Medium  (Low confidence)	High  (Low confidence)

The emerging evidence of impacts of climate change on supply chains, coupled with the known ongoing increase in the underlying climate hazard and changes in the international geopolitical environment, indicates clearly that this risk will increase with time unless there are significant attempts to ensure resilient supply chains. However, whilst the literature is growing on supply chain disruptions due to climate change, it is less developed than for food systems (where examples of climate's impacts on production are available). In addition, despite the disruptions in 2020 due to COVID-19, supply chains largely were resilient.

However, whilst the risk is likely to grow, our qualitative assessment through expert judgement is that through the course of this century we will have to adapt to logistical interruptions to trade, and

so we rate the magnitude of risk to be medium (in terms of tens of millions of pounds lost each year) and likely to remain so into the future. However, in the absence of sufficient adaptation to increasing climate impacts, this risk is likely to increase to high (hundreds of millions of pounds of damage) on a 4-degree pathway. Nonetheless, there are plausible “black swan” scenarios where interruptions to trade may have impacts orders of magnitude greater (see Risk ID10).

## 7.8.2 Extent to which current adaptation will manage the risk (ID7)

### 7.8.2.1 Effects of current adaptation policy and commitments on current and future risks (ID7)

We are not aware of any specific plans or strategies to manage the specific risks associated with the topic of resilient trade systems.

More broadly, there are actions taking place to consider the opportunities for increased exports of goods and services (see opportunity B7 in Chapter 6: Surminski, 2021).

### 7.8.2.2 Shortfall in current adaptation (ID7)

Both EU Exit preparedness planning, and the consequences of COVID-19 have highlighted the strengths and weaknesses of long, just-in-time, supply chains. There are also increasingly frequent calls by global leaders<sup>8</sup>, and attitudinal surveys of citizens, that indicate recognition that climate change, being a risk amplifier, is likely to be implicated in a growing frequency and magnitude of global trade shocks and calls for ‘building back better’ and more resilient systems with ‘resilience headroom’ built in (CCC 2020), post-COVID. It remains to be seen whether this recognition translates into action. The resilience of UK imports to supply-chain disruption from overseas has not been a strong policy consideration. The hazards and our exposure and vulnerability to this risk are therefore thought to be increasing.

### 7.8.2.3 Adaptation Scores (ID7)

<b>Table 7.22</b> Adaptation score for risks associated with international trade routes	
<b>Are the risks going to be managed in the future?</b>	
<b>UK</b>	Partially  (Low confidence)

The economic value of trade is enormous, which suggests it is likely that markets will autonomously invest in resilience building as impacts increase. However, our view is that it is unlikely they will adapt pre-emptively without intervention from policy. Hence our adaptation score is “partially” with low confidence.

<sup>8</sup> <https://www.un.org/en/observances/earth-day/message>

### 7.8.3 Benefits of further adaptation action in the next five years (ID7)

#### 7.8.3.1 Indicative costs and benefits of additional adaptation (ID7)

The resilience of trade to shocks first became an area of focus following the 2007/8 and 2010/11 food-price spikes (Challinor *et al.*, 2016; Challinor *et al.*, 2018), and, of course, COVID-19 has highlighted the vulnerabilities inherent in the trade in some goods. Given that shocks are likely to increase in the future, as climate hazards from extreme events increase, there is benefit from a focus on building further resilience. However, resilience would typically arise from four main properties: building in redundancy (e.g., stocks), diversity (of sourcing, or substitutability), creating modularity or distributed rather than centralised networks, and creating greater flexibility/adaptability. All of these properties have typically been removed to increase efficiency and the leanness of supply chains. Thus, there is a trade-off between fragility (and lower prices) and resilience (and higher prices). As risks increase, the trade-off tips towards resilience providing better returns on average. Resilience as a ‘design feature’ may become a greater focus for investment during post-COVID recovery.

#### 7.8.3.2 Overall Urgency Score (ID7)

Table 7.23 Urgency score for risks associated with international trade routes	
<b>Urgency Score</b>	More action needed
<b>Confidence</b>	Low

The urgency score for this risk is for more action needed (Table 7.23). The resilience of global supply chains, and trade-networks, has come to the fore in the last decade. If supply shocks are likely to increase, focussing on resilience, rather than just-in-timeness, implies potential benefits that may outweigh the costs of increasing redundancy (Tan *et al.*, 2019) (e.g., through decentralisation) or diversity (Kahiluoto *et al.*, 2020; Benton, 2020). Given the opportunities associated with developing new trading relations post-EU exit, coupled with investment in post-COVID-19 economic reconstruction, there is a window of opportunity in the next five years to focus on resilience-building.

### 7.8.4 Looking ahead (ID7)

Without significantly enhanced climate ambition, climate hazards are likely to increase; and with other drivers (e.g., increasing global inequality, less adherence to rule-based cooperation), the resilience of trading networks is likely to be increasingly tested over the decades ahead.

## 7.9 Risks to the UK finance sector from climate change impact overseas (ID8)

An important pathway of transmission of international climate risks and impacts to the UK is through finance. This is separate from the physical impacts which climate change within the UK may have on insurance and investments which are discussed under Risk B4 in Chapter 6, Risk (Surminski, 2021). There may be significant financial exposure to extreme weather (including wildfires) impacts in other countries, especially through the insurance markets and investments. London operates a global insurance market with particular products covering both direct climate change events such as agriculture insurance as well as indirect impacts such as business interruption. Investment risks are clear where domestic owned assets are exposed to extreme weather events in other regions or supply chains are disrupted. This could have a significant impact on all types of asset classes and potentially put further stress on UK pension funds. Transition risks could also appear, and alongside physical risks when particular assets are no longer viable, lead to stranded assets.

### 7.9.1 Current and future level of risk (ID8)

#### 7.9.1.1 Current risk (ID8)

Climate change is likely to have a significant impact on food security (ID1), trade (ID7), the ability of governments to continue to finance public services (Jones, 2014a), and public health across various geographies in the world (ID9). In addition, specific extreme weather events can lead to loss of life, damage to infrastructure, and loss of critical services. The risks from climate change may also be increased as other global risks increase (such as inequality, debt, terrorism, ecosystems collapse amongst others) and the potential for ‘Synchronous Failure’ (Homer-Dixon *et al.*, 2015) is seen (ID10). There are numerous pathways from overseas climate risk to the UK, including many indirect and direct financial impacts. These risks may represent significant financial exposure for the UK especially through the insurance markets, banks, and investments (CFRF, 2020) as it represents a highly networked global system (Mandel *et al.*, 2020).

UK insurance companies may have significant exposure to climate change impacts overseas through physical, liability, or transition risks (Rothwell *et al.*, 2019). London operates a global insurance market with particular products covering both direct climate change events such as agriculture insurance as well as indirect impacts such as business interruption. Changes in morbidity and mortality in overseas countries where UK insurance companies operate could lead to very different risk exposures within life products. Changes to risk exposure of assets and businesses could lead to different general insurance risks. Lloyds (2015) developed a number of scenarios to explore the potential materiality of extreme shocks within the food system and found a number of different scenarios that could impact the UK insurance market.

Investment risks are clear where domestic owned assets are exposed to extreme weather events in other regions. This could have a significant impact on all types of asset classes and potentially put further stress on UK pension funds (Dietz *et al.*, 2016). Indeed, given the highly complex and networked system within the finance sector, an investment risk arising in one economic sector or

institution can cascade to other institutions. Within banking, it has been shown that “*the portion of banks’ loan portfolios exposed to these sectors is comparable to banks’ capital*” (Battiston *et al.*, 2017).

#### 7.9.1.2 Future risk (ID8)

Over the long-term the global exposure to the UK through the finance sector is deemed to be significant as it is highly networked and exposed to risk overseas. For example, global coastal flooding scenarios (Mandel *et al.*, 2020) indicate that by 2080, with global adaptation, the UK is the second most exposed country in the world (with a loss of 0.105% of global GDP in the UK) to financial loss. In the case of non-adaptation, the UK is the most exposed country in the world with a loss of the equivalent of 2.447% global GDP (global GDP in 2019 was \$142 trillion so this would represent over \$3 trillion in losses in that year). However, it is noted that accurately forecasting the impact of climate change on the finance community is difficult and there is a need for a better dialogue between finance organisations and the climate modellers to ensure reliable information, as well as a clear understanding of the limitation of models, is achieved (Fiedler *et al.*, 2021).

As risk increases, if it is managed through adaptation programmes, there is also the potential for an increase in the need for insurance and therefore an opportunity for the UK insurance market to grow (Surminski *et al.*, 2016). Indeed, there is an estimated 1.7 billion people in developing countries who have no access to financial services including insurance (Panda *et al.*, 2020). Insurance can assist countries to recover faster from disasters as well as provide expertise in risk evaluation and exposure (Jarzabkowski *et al.*, 2019). This expertise, especially within re-insurance companies and catastrophe risk modelling organisations, therefore offers growth potential for the UK. However, data on risk exposure and climate change impacts need to be as accurate as possible in order to avoid over or under-pricing insurance products.

There are also significant opportunities internationally for investment into adaption (and mitigation) for UK based firms. For example, UNEP estimates future adaptation needs in developing countries could range from US\$140 billion to US\$300 billion by 2030 and from US\$280 billion to US\$500 billion by 2050 (UNEP, 2018).

#### 7.9.1.3 Lock-in and thresholds (ID8)

The finance system can already be considered as locked-into a global set of processes that require a ‘revolution’ (Jones *et al.*, 2020) within the finance sector in order to respond appropriately to climate risk. There is also a number of climate change threshold events that could have a significant impact on the UK’s finance sector (see for example Lloyds, 2015). In addition, given the networked nature of the financial system (Mandel *et al.*, 2020) any large-scale negative impacts (including bankruptcy) within an individual organisation due to mismanaged risk exposure can cascade through the system quite rapidly and act as a threshold event itself.

#### 7.9.1.4 Cross-cutting and Inter-dependencies (ID8)

There are multiple interacting risks that should be considered and given the finance sector is highly networked this would allow any climate risk exposure to readily propagate through the financial system (Battiston *et al.*, 2017). However, evidence is low with regards to the precise mechanisms for interaction, climate risk exposure and impact. This risk also links to risk B4, Risks to finance, investment and insurance including access to capital for businesses.

#### 7.9.1.5 Implications for Net Zero (ID8)

Evidence is low regarding Net Zero transition risks although more data are being made available through processes including the Task Force on Climate-related Financial Disclosures (TCFD) which should improve our understanding. The changes required to achieve Net Zero can be seen as either a risk or an opportunity for the UK finance sector.

Transition risks could appear and, alongside physical risks when particular assets are no longer viable, lead to stranded assets (Caldecott, 2017). A recent report (Leaton and Grant, 2017) finds that *“\$2.3 trillion of upstream projects – roughly a third of business as usual projects to 2025 – are inconsistent with global commitments to limit climate change to a maximum 2°C and rapid advances in clean technologies.”* This represents a significant risk to UK investment companies including pension funds, although announcements in 2020 by major UK pension funds, such as the National Employment Savings Trust (NEST) and the Universities Superannuation Scheme (USS), will see moves towards divestment of funds away from fossil fuels (in particular coal).

The use of economic evidence such as carbon pricing and economic value of natural capital to include environmental externalities in government policy, financial planning and business decisions is gaining traction (Schultz *et al.*, 2015, Guerry *et al.*, 2015, Azqueta and Sotelsek, 2007) at different rates of development across the world, including in some countries a *“lack of political support by key people”* (Virto, 2018). Valuing the benefits from the natural environment and the costs of the damage from human activities in monetary terms allows for them to be accounted for along with other costs and benefits in business and financial management decision processes. However, it is not possible to estimate the economic value of all climate change risks, biodiversity loss, and all the benefits from nature, and therefore this approach can sometimes be seen as *“ideological”* (Sullivan, 2017) Therefore, economic valuation should, at least, be reported in a transparent way showing the coverage and the gaps, and without disregarding other metrics and approaches. This way we can avoid treating all data as equivalent in balance sheets (Sullivan & Hannis, 2017) and avoid unintended consequences of economic analysis and evaluation of governance responses.

#### 7.9.1.6 Inequalities (ID8)

It is currently unclear how different groups may be impacted by this risk.



## 7.9.1.7 Magnitude Scores (ID8)

<b>Table 7.24</b> Magnitude score for risk to the UK finance sector from climate change impact overseas					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>UK</b>	Low  (Low confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)	Medium  (Medium confidence)	High  (Medium confidence)

Finance risk, predominantly through UK exposures in investment and insurance, is well understood and modelled under present climate conditions where the impact of those climate events follows an expected trajectory. Therefore, the risk to the UK is currently considered low (table 7.24). However, there are many uncertainties on the stability and interconnectedness of the finance sector which means this risk may be considerably underestimated and therefore this is judged as low confidence. In the future, both transition risks and climate change risks will impact a financial market which will by necessity be very different from today (both in terms of use of financial technology, product innovation, further integration between markets, exposure to risks in very different markets, and the adoption of robust risk management practices above and beyond risk disclosure). In the short term (to 2050) an ambitious pathway will increase transition risks (medium) as the finance sector adapts to a new economic reality. Over the longer terms (to 2080) these transition risks will reduce however climate risks without adaption remain and therefore we see risks staying as medium under a 2-degree stabilisation pathway. A less ambitious pathway will see increased climate risk, to high, over the short and long term, as well as more modest increases in transition risks. There is medium confidence in this designation, given that the future of the finance market is integrated into the overall risk of the economy although the exact linkage between climate and the economy is uncertain.

## 7.9.2 Extent to which current adaptation will manage the risk (ID8)

## 7.9.2.1 Effects of current adaptation policy and commitments on current and future risks (ID8)

The UK Government is showing leadership in climate finance. Over the last two to three years there has been a significant increase in regulatory activity to encourage physical risk analysis and disclosure across the financial sector, which is encouraging firms to internalize climate risks, including physical risks. For example, banks and insurers in the United Kingdom are now required to allocate responsibility for identifying and managing climate-related risks to senior management functions (PRA, 2019). Firms should expect that disclosure will be mandated in the near future (Treasury, 2020).

There has been an increase over the last few years in the use of responsible investment (Jones, 2019) and measures such as Environmental, Social, Governance (ESG) metrics to manage investments. As the use of ESG measures becomes more mainstream then indirect and non-material impacts of climate change will become more important. For example, climate change will make more areas water-scarce, therefore reducing the viability of some areas where currently factories are located. Manufacturers' use of local water resources in areas of water scarcity can cause significant competition between factories and the local population (Karnani, 2014). In response, supply chains could shift (due to climate change) and may need to move sourcing. These shifts can increase the social cost of UK imports if, for example, supplies are sourced from areas with poor water governance or poor transparency and regulation. The social impact of the UK's imports may therefore increase, having a negative impact on ESG measures and social acceptability more generally. However, if these changes are well managed then the link to changes in social attitude (BEIS, 2020) can offer an opportunity to amplify a move towards more socially inclusive and climate-friendly business models.

#### 7.9.2.2 Shortfall in current adaptation (ID8)

These actions represent a significant attempt to manage the risks associated with climate change overseas for the finance sector. However, disclosure is only the first step, and these current plans are only sufficient to manage the risks if action is then taken to respond to them.

#### 7.9.2.3 Adaptation Scores (ID8)

Table 7.25 Adaptation score for risk to the UK finance sector from climate change impact overseas	
Are the risks going to be managed in the future?	
UK	Partially  (Low confidence)

#### 7.9.3 Benefits of further adaptation action in the next five years (ID8)

There have been significant shifts in assessing, disclosing, and analysing climate risks and more is expected in light of expected shifts from voluntary to mandatory action driven by regulators. While it is clear that the extent of physical risks is currently low and expected to become significant in the longer-term, there are clear dangers in considering physical risks 'as under control'. There are lock-ins especially within real-estate investment where adaptation measures require further investment.

Whilst there has been improvement in adaptation action from CCRA2, changes have mainly been made in climate risk regulation and reporting as opposed to changing capital flows. Moreover, given the tightening climate policy landscape, there are significant lock-in effects if there is no substantial redirection of financial flows. Whilst banking and insurance sectors have responded effectively to

current extreme weather events, the increase in magnitude and frequency means the likelihood of ‘unhedgeable risk’ is higher – straining the insurance sector. Given that financial risks are still not integrated within firm operating models or in financial markets as a whole, there are still significant systematic risks (Mandel *et al.*, 2020). Whilst companies have started adopting TCFD recommendations, identifying climate risks is only the first step. TCFD’s most recent status update report acknowledges that there needs to be a better understanding of how disclosing climate-related financial information is changing corporate strategies on adaptation, and how investors are using the disclosed information to inform their decisions (TCFD, 2017).

The UK has been seen as a leading power through the passing of the 2008 Climate Change Act, the recent adoption of a Net Zero target, as well as institution building and coordination across government – though less so on climate change adaptation (CCC, 2019). With the UK set to host the 26<sup>th</sup> Conference of the Parties of the UNFCCC (COP26), there is also an aspect of this risk about showing leadership on managing the risks to finance from climate change. A critical issue to tackle at COP26 is the existence of a global green finance gap and many in the finance sector highlight the uncertainty over national and international climate policy as a key factor in this gap (Hafner *et al.*, 2020).

#### 7.9.3.1 Indicative costs and benefits of additional adaptation (ID8)

It is difficult to estimate the potential costs and benefits of further adaptation. However, what is clear is that the potential risks to the financial markets in the UK from climate change are extremely large, and because of the role of UK financial services, very large for the UK. Dietz *et al.* 2016, using a Monte Carlo simulation of the DICE model, estimated the present value at risk as a result of climate change under a business-as-usual pathway to global financial assets as \$2.5 trillion (mean expected losses, discounted in present value terms) between now and the end of the century, and still \$1.7 trillion under a 2°C pathway. However, under business as usual, the 99<sup>th</sup> percentile tail risk is \$24.2 trillion. A sizeable amount of global financial assets are managed by the UK financial markets. There are existing voluntary initiatives (TCFD) that are helping to increase the disclosure of these potential risks, but as highlighted in Chapter 6 (Surminski, 2021), there appears to be less action on adaptation.

#### 7.9.3.2 Overall Urgency Score (ID8)

Table 7.26 Urgency score for risk to the UK finance sector from climate change impact overseas	
<b>Urgency Score</b>	Sustain current action
<b>Confidence</b>	Low

The risks to UK finance from climate change overseas were previously included in the CCRA2 Evidence Report within other risk categories. However, with an increasing international reputation for climate finance, increasing evidence that London, as a finance centre, is a key strategic risk to the UK economy, and increasing evidence of financial risk from climate impacts around the world, it is important to highlight this as a specific risk area for consideration going forward. This current effort,

led by the UK Government, should lead to a better understanding of the risk exposure within the finance sector and then to a reduction in the risk through further action. Given this current effort and the substantial increase in action since CCRA2, we recommend the urgency score for this risk is to sustain the current action (Table 7.26). However, this is based on the assumption that the UK Government will maintain its commitment to grow its efforts against this risk and while there remains uncertainty around exactly how these risks manifest, we have low confidence in this being sufficient over time.

In addition to wider financial risk, there is a case for renewed efforts on climate finance directed at helping countries protect their vulnerable populations. This would build on the UK's previous commitment to spend at least £5.8 billion of International Climate Finance (ICF) between 2016/17 and 2020/21. These actions would engender the alliances between the UK and the climate-vulnerable nations that are needed in order to ensure UK leadership and legacy in climate negotiations. It would also improve the UK's global standing and reduce the overall risk exposure of the UK's finance sector.

#### 7.9.4 Looking ahead (ID8)

Longer-term increased pressure from growth in global demand for all resources, as well as growth in the UK finance and insurance sector exposure through international expansion, would make the risk from climate-related shocks in other countries, and consequent cascading risks, more likely and larger. However, it is not possible to quantify these risks at present given the interconnected and speculative nature of the precise scenarios associated with this global demand growth and UK finance sector expansion.

### 7.10 Risks to UK public health from climate change impacts overseas (ID9)

This section examines mostly the threat of vector-borne disease (VBDs) to the UK arising initially from human infections acquired abroad and import of infected vectors or animals. There are two factors that determine climate-induced VBD risk: emergent favourability of overseas climate and prevalence. The risk is high where the vector has been introduced recently and become endemic. There are a number of examples where UK visitors to parts of Western Europe now bring the risk of exposure to diseases, that until recently were only found in the tropics thus long-haul destinations. The UK climate is also relevant, since it may change enough to allow local transmission of these diseases by vectors that transmit the infection human to human or to a further host from that initially overseas infected person (see Chapter 5: Kovats and Brisley, 2021).

## 7.10.1 Current and future level of risk (ID9)

### 7.10.1.1 Current risk (ID9)

The risk considers the introduction of an infectious disease from outside the UK within the remit of the impacts of climate change (the people and wellbeing transmission pathway in figure 7.1). The emphasis is on vector-borne disease risks as these are diseases that have been shown to spread due to climate change and climate variability (see also Chapter 5: Kovats and Brisley, 2021).

Of the existing infectious diseases with known climate drivers, the most likely to impact the UK are those transmitted by animal vectors. (but there are always risks from novel emerging diseases, such as COVID-19, for which there may be an increased probability of emergence due to climate change, see Box 7.1). These vectors are normally blood-sucking arthropods, namely mosquitoes, midges, and ticks, for human and domesticated and wild animal diseases. In some cases, birds are the possible introducer of the pathogen (Medlock *et al.*, 2005), but the local climatic conditions have to allow the transmission of that pathogen by the vectors, and to date, this has been observed in the UK more for insects than other types of vector.

#### 7.10.1.1.1 Vector borne diseases

For a vector-borne disease to emerge then three key factors have to be in place: 1. The vector has to be present or introduced and able to establish and thus reproduce and, in the UK context, it thus needs to be able to overwinter outside its active period; 2. The pathogen has to be present or introduced and have a competent vector in the same location to enable transmission; 3. The host (human or, normally, other warm-blooded animal) has to be accessible by the vector and susceptible to the pathogens. The pathogen can be a bacterial, virus, or in the case of malaria a protozoa. Although malaria has been transmitted historically in the UK and was not eradicated until the early 1900s, almost all cases found today have been contracted overseas. Therefore, it is not considered here as it can be easily treated if recognised by the patient and medical practitioner (see also Chapter 5: Kovats and Brisley, 2021 for an assessment of the risk of local transmission within the UK).

Climate is important for the risk magnitude because the life cycle, development, and reproduction rate of the vector has absolute limits imposed by the thermal climate. Additionally, it often needs rainfall or other sources of small-sized water breeding sites. Most importantly the pathogen development in the vector is driven by temperature and has, normally, a much higher initial threshold for development than the vector itself. So, the vector can be present, but the climate is often not warm enough for the effective development of the pathogen within its body (Medlock and Leach, 2015).

#### 7.10.1.1.2 Risk to public health from climate-related emerging diseases transmitted to UK

The main risks for UK public health from climate change impact overseas are through travel and people movement. Climate change impact overseas increases the presence of diseases in more areas, which means more of the UK population travelling overseas may be exposed and bring these health risks (e.g., vectors) back to the UK. This, in combination with the UK climate becoming

increasingly suitable as a host to these diseases, has enhanced the risk of emerging diseases (with overseas origins) within the UK.

Vector competence is the ability of European and UK endemic vectors to transmit currently exotic pathogens, particularly viruses. Mosquitoes are an example of a specific public health risk with origins overseas. The risk exists independently of climate change, but warmer temperatures would allow longer transmission seasons. The UK has the Anopheline mosquito species, which is capable of transmitting malaria and has done so historically (Kuhn *et al.*, 2003). The most competent malaria transmitter was *Anopheles atroparvus* which is widespread (Snow, 1998). Blagrove *et al.* (2016) found that the mosquito *Ochlerotatus detritus* (*Aedes detritus*), whose habitat is brackish water, is competent for West Nile virus (WNV) but not for dengue virus (DENV) or chikungunya virus (CHIKV). With a highly effective health service and effective treatment and control, malaria is unlikely to re-establish in the UK (see Chapter 5: Kovats and Brisley, 2021).

The two mosquito species giving more immediate concern are *Aedes albopictus* and *Culex modestus*. *Aedes albopictus* is not endemic in the UK but has spread around the world, often in the trade of used tyres, from its original SE Asia home to many tropical and more temperate parts of the world. This mosquito is a competent vector of several arboviruses that affect humans, including chikungunya, dengue and Zika viruses. It has been discovered multiple times in Kent but is not established. This mosquito appears to be able to adapt to non-tropical climates (Waldock *et al.*, 2013). Using a modelling approach for the UK, Metelmann *et al.* (2019) suggested that the current, warmed climate may be sufficient to currently sustain and increase the area around the Thames estuary for this mosquito.

*Culex modestus* is a competent vector of West Nile virus (WNV) and was found established in two marshland sites of the Thames Estuary (Golding *et al.*, 2012). It has since been found at other sites in SE England (Public Health England, 2018) and is spreading in East Anglia (Medlock and Vaux, 2012, Hernández-Triana *et al.*, 2020). It is seen as the main bridge vector between birds and humans and other animals, e.g., horses, in the transmission of WNV. Human cases have been recorded in continental Europe. WNV could be introduced to the UK by migrating birds and serological evidence of WNV infection have been found in birds in the UK (Buckley *et al.*, 2003). In 2019 there were 834 cases of WNV reported in humans in the US. Based on the rapid spreading in the US causing 2000 deaths, from New York City in 1999 to southern California in 2003, it is reported to cross about 1000km per year when competent vectors are present (Hadfield *et al.*, 2019, CDC, 2019). These competent vectors include *Culex tarsalis* and *Culex pipiens* (Hadfield *et al.*, 2019). In the UK, we have *Culex pipiens pipiens* but is understood to be predominantly bird biting and is unlikely to act as a bridge vector between birds and humans according to Public Health England (2017). However, they do identify *Culex modestus* as a potential bridge vector with overall low to moderate risk.

The recent discovery of ticks carrying tick borne encephalitis virus in the UK is a further indication that exotic diseases are becoming established in the UK (Holding *et al.*, 2020).

#### 7.10.1.1.3 Existing vector-borne diseases illustrate risk transmission pathways to the UK

Some existing diseases – whether or not they are linked to climate change - provide examples of how interconnected risk cascades can operate, potentially illustrating the unpreparedness of the UK to climate-related vector-borne transmissions. One such example is African swine fever. Although this virus can be spread through ticks of the genus *Ornithodoros*, these ticks are only found on the Iberian Peninsula in Western Europe. Transmission of this highly contagious disease is animal to animal, infected clothing or boots and in contaminated meat products (movement of goods, people, or wellbeing transmission pathways; c.f. Fig 7.1). Outbreaks in Europe as of August 2020 are as far west as Slovakia and Poland, and more recently Italy, in both swine production units and wild boar populations (World Organisation for Animal Health (OIE), 2020a, b). Wild boar cases have been reported in Belgium in summer 2019 although the numbers seem to be diminishing (Defra, 2019a). The ongoing outbreak in SE Asia is of concern to UK authorities (Defra, 2019b), CNN reports 100 million pigs in China have been lost to the outbreak (CNN, 2019). The fear in the UK is that through contaminated meat the virus could spread to small scale pig producers, hobby farmers or the introduced wild boar population. Outside the tropics, the distribution may well have climatic controls (Donaldson *et al.*, 2016) in the United States, and in its natural infectious cycle outside intensive pig production in Europe (Chenais *et al.*, 2019).

#### 7.10.1.1.4 Lessons from COVID-19 for vector-borne diseases

The disease COVID-19 and the SARS2-CoV-2 virus that causes it gives a good insight into how an endemic, indeed pandemic, of an infectious disease, can challenge society when the human-to-human transmission is operating. As a result, there is now a much better understanding of how an infectious disease develops within populations not previously or recently exposed to such pandemic. Epidemics follow a natural curve that rises, peaks, and decreases (Giordano *et al.*, 2020). In the UK, the reduction in peak and reduction of overall cases came through restrictions of social activity and the lockdown. Further waves can form as long as there are still cases or there is no effective vaccination. Health services have finite capacity and thus controlling the peak is very important. Test and trace is essential to detecting outbreaks and contacting people who have been infected especially if they are asymptomatic (Wells *et al.*, 2020). We also know that other diseases and conditions go untreated or undetected leading to an increase in non-COVID-19 deaths currently or in the months ahead e.g., cancer (Maringe *et al.*, 2020). We must not forget the psychological impacts, and these may impact not just in months but over years into the future, creating indirect effects or risk cascades.

What can we learn from COVID-19 for VBDs? The initial spread of VBD is likely to be slower than COVID-19. However, in the case of blue tongue, it was driven by animal movements and initially not recognised. Blue tongue is a viral disease of ruminants spread by the midge vector of the *Culicoides* genus. The spread of VBDs can be accelerated if, for example, a family returned to the UK with an exotic viral disease and has human-to-human contact with the summer holiday tourist influx (a clear issue with COVID-19). Furthermore, overseas visiting populations spending time outside and among local populations could be prime locations for the infection to cross over between populations. This can be brought back to the UK along with the movement of people transmission pathway, as was the case with COVID-19. Therefore, it is the movement of humans rather than the vector itself that will

spread the disease. Further, the geography of VBDs is changing in Europe, which means UK visitors to the EU can be increasingly at risk and are more likely to bring VBDs to the UK.

#### 7.10.1.1.5 Mental health issues arising from climate change impacts overseas

Climate change is a factor that is adding to mental health and wellbeing challenges (Berry *et al.*, 2010). Indicators of health and wellbeing, while being shown to not increase above a certain level of GDP per capita, can be enhanced through a range of other socio-environmental factors such as access to nature (Maller *et al.*, 2006; Pretty *et al.*, 2016). Societal groups, in particular young people, have increasingly expressed despair at seeing and hearing the impacts of climate change which so far have been more severe outside the UK in terms of human and ecological impact, through the increasing IT & information transmission pathway, and their helplessness to change it, as is often demonstrated and expressed through participation in climate activism. Social amplification or attenuation, through societal response, will therefore become increasingly important. Young people are particularly vulnerable as they have fewer resources and strategies to cope with this challenge to their wellbeing, and patterns of mental health in children and teenagers is also an important determinant of mental health in adult life (Carod-Artal, 2017). In a broader societal context, climate change discourse can lead to community level division and fractionation, which can impact the community-level mental health and wellbeing.

The impact on mental health can be measured based on the level of “feeling secure” and “quality of life”. As evidenced in a recent review, the indirect impacts of the mere fact that climate change is occurring on mental health “*are no less serious because they can [contribute] to disorders, such as depression, antisocial behavio[u]r, and suicide*” (Clayton *et al.*, 2017). Climate change impacts abroad such as loss of life and biodiversity may add to this stress. A sense of wellbeing for UK citizens may also be attached to their leisure time and, for example, an ability to travel and interact with nature in other parts of the world (as is evident from COVID-19's impact on overseas vacations in 2020: Flaherty and Nasir 2020). If iconic and meaningful assets, such as the coral reefs are lost, or there is an increase in turbulence making flights less comfortable (Williams and Joshi, 2013) and there will be some degradation of this sense of wellbeing through travel.

#### Box 7.4 Case study of risks from competent UK vectors

The spread of dengue from nine countries a few decades ago, to being endemic for almost half the world's population today, is highly relevant to ongoing climate-induced risks. Especially, since people continue to travel and return from these areas (Hosangadi, 2019). These changes in the distribution of dengue are probably in part driven by climate change, urbanisation and the ability of *Aedes spp.* mosquitoes to thrive within polluted water of rapidly expanding urban areas mostly in the tropics and sub-tropics give wider cause for concern.

Further areas of concern include the spread in the U.K. the spread of *Culex modestus* (a competent vector of West Nile virus, WNV) from its recently-found but established marshland sites of the Thames Estuary to a wider area; the discovery of the virus that causes tick born



encephalitis in 2019 for the first time in two places the UK; and the regular introduction and detection of *Aedes albopictus* in Kent.

The autochthonous (locally acquired) cases of dengue in Spain and France reported in September 2019 due to *Aedes albopictus* (ECDC, 2019), the 2017 local outbreak of chikungunya virus in Italy, 2017 (Lindh *et al.*, 2019) and Italy's first autochthonous dengue outbreak in August, 2020 (Lazzarini *et al.*, 2020); are real wake up calls. These outbreaks have shown how vulnerable mainland Europe, frequently visited by UK travellers (movement of people transmission pathway) is to the introduction of what were seen previously as tropical diseases.

#### 7.10.1.2 Future Risk (ID9)

The frequent reintroduction of *Aedes albopictus* (a species of mosquito), although probably not fully established, with its ability to adapt to cooler climates suggests that relatively small upward shifts in temperature along with a future run of warmer summers extending into warmer autumns may well allow this mosquito to spread. This mosquito can transmit a number of viruses to humans including dengue and chikungunya (Metelmann *et al.*, 2019). Although at present a more geographically limited threat in the UK, *Aedes* mosquitoes thrive in urban areas making London at increasing risk of establishment.

As climate change impacts overseas increase, there is the potential for increased anxiety for people about family and friends being exposed to risks overseas, for interruptions to travel, or disrupted journeys, or events happening whilst people are on holiday (Flaherty and Nasir, 2020), or about environmental degradation (Cunsolo & Ellis, 2018).

#### 7.10.1.3 Lock-in and thresholds (ID9)

No clear issues with lock-in or thresholds have been identified.

#### 7.10.1.4 Cross cutting risks and Inter-dependencies (ID9)

There are interdependencies between disease risk, trade, and the movement of people – as these are potential routes for the introduction of diseases and vectors to the UK. This is in addition to climate-related movement in vector ranges, and the relationship between climate and the emergence of new diseases. Surveillance at borders – particularly after EU-Exit – is therefore of increasing importance.

#### 7.10.1.5 Implications for Net Zero (ID9)

Within the UK, habitat changes, especially wetlands, need to be actively managed, so they do not become an emerging breeding ground for newly-arrived vectors. This is also the case for the creation of urban green and blue spaces and the development of Sustainable Drainage Systems (SuDS) in urban and peri-urban areas with high population densities and recreational usage. There is therefore a potential link to extensive use of SuDS as a strategy within Net Zero commitments.

## 7.10.1.6 Inequalities (ID9)

COVID-19 has also illustrated how socio-economic conditions can impact disease transmission and risk. Here, vulnerability refers to how this risk might impact the most vulnerable population within the UK, and risks increasing inequality i.e., lower economic households having less capacity to cope, or those already vulnerable in terms of health. A combination of these vulnerabilities leads clearly to multidimensional vulnerability. COVID-19 and probably most infectious diseases have much higher risk and more severe outcomes for the elderly, or people with existing health conditions, such as immunosuppression. For vector-borne diseases that might emerge, it may show different socio-economic patterns, especially for vectors that do not thrive in cities. Here it may affect more people who can afford to be outside in areas where the vectors can thrive. For urban adapted vectors, it is likely to impact the poorest, living in substandard housing, with a higher number of inhabitants per room or building, and possibly working outside thus increasing their exposure to the vector.

## 7.10.1.7 Magnitude Scores (ID9)

<b>Table 7.27</b> Magnitude score for risk to UK public health from climate change impact overseas					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>UK</b>	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)

See explanation in ID1 for similar future scenario magnitude scores.

Over the last decade the world has seen emergence or re-emergence of COVID-19, SARS, Ebola, Zika. All have led to significant interruptions resulting in high impact in terms of costs as defined in Table 2.2 in Chapter 2 (Watkiss and Betts, 2021). Similarly, whilst in any given year the risk may be low, it increases in magnitude as time goes on. Some of these health risks had strong climate drivers e.g., the Zika outbreak in Brazil. The direct impact on the UK for these outbreaks has ranged from minor to great, and where not directly impacted, the UK has often been active in providing assistance. The magnitude of impact this risk presents means the magnitude score for the current risk and future risk are both High (with medium confidence).

## 7.10.2 Extent to which current adaptation will manage the risk (ID9)

### 7.10.2.1 Effects of current adaptation policy and commitments on current and future risks (ID9)

Controlling vector-borne diseases entering the UK is the focus of adaptation for this risk (for risk H8, the assessment looks at controlling vectors and diseases once they have entered the UK). EU Exit could make entry checks more challenging if there is a decrease in the work with and access to the European Centres for Disease Control (ECDC). At this stage (time of writing), it is unclear if the UK will remain part of international public health surveillance systems including the ECDC.

Border surveillance is also critical to dealing with the international dimensions of climate-related UK public health risks. This is occurring, but again it is difficult to determine on the basis of the evidence available how much is happening and what types of vectors or diseases are being screened for, and if any are not that should be in the next five years. National checks and surveillance of vector species is determined by the resources to spend on 1) tick recording schemes (TRS) and 2) surveillance by Public Health England (PHE) of endemic and invasive mosquitoes at ports of entry (e.g., used tyres checks). Chapter 5 (Kovats and Brisley, 2021) provides more details on this and on adaptation for diseases emerging within the UK.

### 7.10.2.2 Shortfall in current adaptation (ID9)

Although established monitoring systems are in place, given the uncertainties over the extent of checks at UK entry points, there is an argument for enhanced surveillance of both exotic vectors and pathogens at UK entry points. Further work on vector competence (to what extent vectors are carrying and transmitting diseases when they enter the UK) is also required. Further work on modelling the risk of emergent vector-borne disease due to climate change is needed.

### 7.10.2.3 Adaptation Score (ID9)

<b>Table 7.28</b> Adaptation score for risk to UK public health from climate change impact overseas	
<b>Are the risks going to be managed in the future?</b>	
<b>UK</b>	Partially  (Low confidence)

### 7.10.3 Benefits of further adaptation action in the next five years (ID9)

#### 7.10.3.1 Indicative cost and benefits of additional adaptation (ID9)

Actions to promote adaptation to emerging diseases include:

- More real-time monitoring of air travel routes, transmission pathways of movement of people and goods.
- Communicate outdoor risks if a vector-borne disease is introduced.
- Improve training and awareness of primary health care practitioners.
- Raise the levels of surveillance programmes and some random screening (for example, part of blood donation screening for antibodies).
- Improvement of public and professional level information, transmission pathway IT/information.

There would be benefits from increased surveillance of wildlife, people or other imports (e.g., used tyres) coming into the UK, which comes with increased costs. However, if newly arrived infected vectors or animals in combination with a more favourable UK climate leads to local transmission, the cost of the impacts may be a lot more. COVID-19 has provided a good example of the scale of impact costs and how this can cascade into other sectors. Therefore, it shows that investments in surveillance can pay off to avoid high impact situations.

It is not clear how the UK could fully protect itself from risks from emerging diseases overseas that have a transmission pathway to the UK. Targeted public information, advertisements in holiday destinations about outbreaks, and more information or advertisements in in-flight magazines would support this effort. Further actions include improving seasonal forecasts of conditions for the establishment of vector-borne disease, especially the extension of summer-like conditions into the autumn; improved awareness of risks at both primary and secondary health care; better monitoring and surveillance of potential vectors in the UK, especially for virus antibodies.

Actions can also be taken that target key overseas areas, i.e., monitoring and research in areas overseas that are likely to be prone to the emergence of new infectious diseases both vector-borne and other contagious diseases. Ongoing collaborative research and monitoring are critical if imported health risks are to be avoided. One key challenge for research comes from EU Exit: in the past, the European Commission funded many of these integrated projects involving environmental and social controls and impacts of infectious diseases. If this funding source becomes closed to the UK, then these opportunities will need to be replaced by UK funding if we are to continue to engage in this pool of expertise and knowledge production.

#### 7.10.3.2 Overall Urgency Score (ID9)

Table 7.29 Urgency score for risk to UK public health from climate change impact overseas	
<b>Urgency Score</b>	More action needed
<b>Confidence</b>	Medium

The urgency score for this risk is for more action (Table 7.29). This score has been given because of the potential for significant impacts from emerging diseases if new vectors or pathogens enter the UK and then become established. Although established monitoring systems are in place, given the uncertainties over the extent of checks at UK entry points and the high level of potential risk, there is an argument for enhanced surveillance of both exotic vectors and pathogens at UK entry points.

#### 7.10.4 Looking ahead (ID9)

The longer-term risk from vector-borne diseases probably revolves around the spread of mosquito vectors already identified, although the potential for an endemic species to be competent in the spread of an exotic pathogen e.g., an arbovirus cannot be ruled out. COVID-19, although SARS2-CoV-2 is not vector-borne, has shown how an emerging disease can disrupt the nation and lead to a death rate on a level not seen since wartime. As detailed in this section the world has seen a number of emerging diseases or introduction of diseases endemic elsewhere in the world, which move country to country. Some of these have been introduced into the UK. It is **certain** there will further emerging diseases, some of which could have even bigger impacts than COVID-19 and be introduced to the UK and could also disrupt the UK economy from overseas through changing supply chains, trade, people movement and so on. The world needs to learn and remember what is needed for the next time, but also there is a need for much better preparedness and more pro-active research into emergent diseases and research and training into their containment. Our view is that the recent funding cuts and reorganisation of government departments have reduced the UK's capacity as a nation in this area. The UK needs to seriously consider the importance of disease (re-)emergence as a risk to the health and economy of the UK, including potential risk cascades, and systematic risks, and how well that work in this area is funded.

### 7.11 Systemic risks arising from the amplification of named risks cascading across sectors and borders (ID10)

Whilst the risks above focus more on “sectoral risks”, there is the potential for hazards to create cascading risks that cross sectors and geographies through contagion. COVID-19 is an example (see Box 7.1): the emergence of the disease may have an attributable component from climate change, but the spread of the disease, and attempts to mitigate it have created disruptions in demand, in trade through supply-chain disruptions from changes in labour availability, through people movement and broader economic impacts. These multidimensional impacts affecting multiple sectors and all countries are an exemplar of “systemic risks” arising from highly inter-connected sectors and economies.

This chapter has addressed a range of international climate risks with impacts across food production systems, international violent conflict, human movement, trade, markets and finance, health, and governance. The framework outlines how these risks can interact geographically and via teleconnection, through various pathways to arrive in the UK. Therefore, the interconnectedness of considered risks (ID 1-9) evidences a need for a more joined-up assessment of the systematic risk of

international climate change to the UK, which is more than just a sum of each individual risk. This is ID10: Systemic risk arising from the amplification of named risks cascading across sectors and borders.

Processes of social amplification and risk interactions or cascades are often missing from narrow or sector-bound risk assessments that are relied on for decision-making (Challinor *et al.*, 2018). This issue was documented by Renn (1998) but also emerged from the synthesis of evidence conducted per risk in this chapter. The risk assessments and evidence that we have reviewed under each risk heading often contain sector-specific studies that miss the bigger picture and therefore may underestimate the threat arising from the impacts of climate change. The capacity for a systemic risk assessment is therefore still limited by siloed and disciplinary evidence bases these assessments are founded on.

The need to be cognisant of systemic risks is growing for three reasons:

1. Systemic risks arise from a combination of local feedbacks and larger-scale events within tightly coupled systems, and whilst they may have a “trigger” - a climate hazard, for example, the trigger itself is not the “cause” rather the catalyst, and causation arises from a concatenation of multiple circumstances (e.g., food price spike arises if there is pressure on the system if there is a lack of transparency about stocks and the perception of an unexpected event; the event itself, under other circumstances may have little impact). Emerging literature, and the experience of COVID-19, provides a stronger body of knowledge of systemic risks (see Challinor *et al.*, 2016; Adger *et al.*, 2018; Centeno *et al.*, 2015; Gaupp *et al.*, 2020; IRGC, 2018; Peters *et al.*, 2015; Vié and Morales, 2020). A corollary of this body is there is no simple linear mapping of hazard to impact: as detailed in multiple places above the same hazard above can have different outcomes depending on the circumstances. It is not easy therefore to forecast specific risks, rather recognise the potential for systemic events and build resilience in.
2. The experience of cascading risks over the last decade or so (see references above and Table 7.30) has highlighted that the global interconnectedness of the system, the just-in-time nature of supply chains, and more unstable global geopolitics has made the systemic fragility greater than hitherto. In particular, the costs associated with disruptions arising from cascading risks from supply chains can be much greater than the direct costs of the hazard itself (Inoue *et al.*, 2019). Estimates of the economic costs of COVID-19 range from USD3.3-83 trillion (Centre for Risk Studies University of Cambridge Judge Business School, 2020), of which only a small fraction is the direct healthcare-related costs (Tan-Torres Edejer *et al.*, 2020). In the UK context, Lilly *et al.* (2020) estimates the economy-wide cost of COVID-19: the economic cost, as measured by an increase in public borrowing, is projected at over £300bn, the increase in the budget for healthcare (via the NHS) is ~£5bn).
3. Climate hazards, associated in particular with extreme weather are becoming more prevalent: extremes are getting more extreme and more frequent, and with noticeable teleconnections (e.g., the extreme Delhi freeze and Australian drought at the end of

2019 are linked to an “extremely positive” Indian Ocean dipole (Wright *et al.*, 2020); 2019 was also a year for record wildfires in N and S America, Australia, Indonesia and Siberia (Huffington Post, 2019)). Attribution science is also highlighting the relationship between extremes and climate change (Carbon Brief, 2020). Hence, some hazards are getting more frequent, more severe and perhaps more likely to co-occur.

All in all, our view is that the evidence from the wider risk literature is that the potential for systemic risks is growing through a more inter-connected world, where risk transmission mechanisms allow risk cascades that lead to system-wide consequences. Systemic risks are, by definition, very significant risks and are often orders of magnitude more impactful than any direct and local risk arising from a climate hazard within a given country. However, by the nature of this topic, there are insufficient examples that link specific events (hazards) to specific impacts in a way to generate broad general conclusions about patterns. Climate hazards arise with quantifiable accuracy and uncertainty and can be projected forwards, but the vulnerability and exposure are complex social/political/economic (or more complex ecological/social/political /economic) functions that are probabilistically unquantifiable. Systemic risks are therefore unlikely to be amenable to standard risk assessment approaches (Challinor *et al.*, 2018). Rather, assessment of this area suggests that there is significant evidence for systemic risks to be ‘sparked’, from a very wide variety of hazards due to climate change (from low probability/high impact extremes or a combination of higher probability/low impact events) interacting with multitudinous drivers and contexts.

### 7.11.1 Current and future level of risk (ID10)

#### 7.11.1.1 Current risk (ID10)

Examples given for ID1-9 in this chapter - summarised in Table 7.30 - have evidenced the systemic nature of international climate risks to the UK. These exemplify the transmission of risks across geographies and teleconnections, sometimes through complex and non-linear cascades. Many included examples also illustrate that social amplification of a hazard can have a greater significance than the initial direct impact.

Examples of risks that have cascaded into creating a systemic risk include the Great-East Japan Earthquake and Tsunami which inundated Fukushima, a disaster unconnected with climate change. Whilst the tsunami and radioactive leak had (primarily) local effects, the wider impacts were greater: the nuclear leak affected power generation, the wider economy, oil prices, and the stock market, with global effects. Car and electronics manufacturers worldwide were impacted due to the reduction in the availability of Japanese-produced parts (Scheffran, 2015). Another example is the 2007/8 financial crisis and its cascading, contagion on the global financial network, leading to impacts through recession, debt, and austerity which lasted over a decade. The final example is COVID-19, the global pandemic. Global estimates of the economic cost of the ongoing pandemic include plausible worst cases of over \$80 trillion (Centre for Risk Studies University of Cambridge Judge Business School, 2020).

**Table 7.30** Examples of risk transmission mechanisms. Systemic risks arise if a hazard (climate-induced disaster, or a hazard arising from climate change) is sufficiently large that it passes along multiple pathways, crossing geographies, sectors and impacts economic and societal fundamentals.

Example of risk transmission		Type	Transmission Pathways	Reference
From	To			
Production in Spain affected by weather	Salad shortage in the UK	Geographically	Movement of Goods	BBC News, 2017a; Guardian 2018
Failure to find consensus in international climate agreement	Anxiety or loss of wellbeing, protest and loss of trust in governance systems in the UK	Teleconnection	Information and IT, Governance	Cunsolo and Ellis, 2018
Local health impacts from an emerging disease (e.g., COVID-19)	Loss of finances and business failure in the UK	Teleconnection & Cascade	Movement of People, Information and IT, Finance	See ID9
Water scarcity in Coca Cola production region in India caused by changing weather, and local failure of governance process to resolve tension or conflict	Loss of custom and damage to reputation in the UK	Teleconnection & Cascade	IT and Information	Karnani. 2014
Inclement climate conditions during Syrian conflict	Asylum applications increased, contributing to political tensions in the UK	Geographically	Movement of People	Abel <i>et al.</i> 2019
Chinese COSCO shipping via Arctic following ice melt	Increase in commercial trade routes such as wind turbine equipment delivery in the UK	Geographically	Movement of Goods, Markets	See ID6
Assets exposed to more extreme weather events abroad	UK investments risks and pension funds	Teleconnection & Cascading	Finance	Dietz <i>et al.</i> 2016

Due to the potential for hidden tipping points and the unpredictability of systemic risks, the learning-from-doing model of conventional risk governance has limited applicability in the confrontation of systemic climate risks to the UK. Instead, guidelines for dealing with systemic risk advise an iterative and ongoing process of governance, which requires “strong leadership and the willingness to adapt



or revise processes, focus on mid- and long-term issues, and accept and resolve trade-offs" (page 17. IRGC, 2018). Whilst this particularly applies to ID10, in a sense, most of the preceding risks have the potential to develop into systemic risks via risk cascades, and governance adaptability is therefore, a generic need for this chapter. To understand the potential impacts of systemic risks, assessment methods have to identify the low probability and high consequence risks (or combinations of higher-probability events that may create systemic shocks) as well as the more commonly studied 'high probability' risks. Methods often applied to this end include using scenarios or storylines to understand the full scope and intensity of a risk and to visualize how a risk may evolve beyond the range of experienced previous outcomes (ibid.).

Systemic risks arise when a hazard leads to risks that cascade across sectors and lead to an overall systemic impact. The focus of this risk is on systemic impacts arising from the transmission of risks from overseas through the movement of goods, people, information, finance, governance issues, etc (Fig 7.1). Managing this range of flows is typically a combination of HMG/reserved control and devolved control. The Internal Market Act (2020), and EU Exit has changed the way goods flow into and out of the UK and also within the UK. The availability of some goods in Northern Ireland has been reduced in the weeks following the end of the transition period in early 2021. COVID-19 has illustrated the complexity of the governance of systemic risk within the UK, with the different regions being differentially exposed to, vulnerable to risks, and responding differently in their actions to mitigate risks.

#### 7.11.1.2 Future Risk (ID10)

The investigation of systemic risk is an active field, and our understanding is advancing fast, as is our collective interest to deal with it (sparked by the events of the last decade outlined above, plus COVID-19). However, the extent to which we will manage to "build back better" to increase systemic resilience is highly uncertain. As highlighted in multiple places above, the risk depends on the hazards (which are increasing), exposure (the degree of embeddedness in global networks and their fragility, which has increased in recent decades and is likely to continue to do so; coupled with geopolitical stability, which may increase or decrease e.g., TIME, 2020), and the vulnerability (which in part depends on supply chain functioning, but also national income and inequality: sudden changes in price impact the poorest most; thus vulnerability may well increase in the post-COVID era). Hence, our view is that systemic risks are likely to increase in the future.

#### 7.11.1.3 Lock-in and thresholds (ID10)

As highlighted in ID1 above, our economy is a complex system that creates its own lock-ins (the "wrong sort of resilience": Oliver *et al.* (2018)); making adaptation to rapid changes difficult. It is axiomatic in complex systems that change happens in 'saltations' or 'punctuated equilibria': a stable configuration remains stable in the face of changing drivers or small-scale perturbations until it passes a threshold, or is perturbed sufficiently, and reconfigures in a new state. COVID-19, coupled with EU-Exit, is creating an economy-wide perturbation that has caused many local-lock-ins to be deconstructed. This provides a timely window of opportunity to help reconfigure the system in new ways – 'build back better'. However, if this window closes and we reconfigure into the previous business as usual state, the opportunities for adapting to, and therefore mitigating, the risks

discussed above become more difficult, particularly that dealing with systemic risks calls for building resilient economies and societies.

#### 7.11.1.4 Cross-cutting and Inter-dependencies (ID10)

This risk arises from inter-dependencies across time, space, and sectors.

#### 7.11.1.5 Implications for Net Zero (ID10)

The main relationships to Net Zero commitments are (a) the extent to which focus is on narrow-sense productivity growth, through efficiency, to reduce emissions, as this may lead to reduced resilience via reduced functional redundancy, and (b) the extent to which Net Zero leads to price rises, which increases the vulnerability of low-wage households.

#### 7.11.1.6 Inequalities (ID10)

Systemic risk leads to society-wide impacts that are broadly felt, but by their nature impact most on the most vulnerable: the elderly, infirm, and economically marginalised.

#### 7.11.1.7 Magnitude Scores (ID10)

<b>Table 7.31</b> Magnitude score for systematic risk arising from the amplification of named risks cascading across sectors and borders					
<b>Country</b>	<b>Present Day</b>	<b>2050s</b>		<b>2080s</b>	
		<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>	<b>On a pathway to stabilising global warming at 2°C by 2100</b>	<b>On a pathway to 4°C global warming at end of century</b>
<b>UK</b>	High  (High confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)	High  (Medium confidence)

By their nature, specific events and how they may cascade through socio-economic and political systems are inherently unpredictable and unquantifiable and by definition, the risk magnitude is “high” as a systemic risk is likely to have economy- and society-wide impacts. However, there are potentially a very large number of hazards that could drive systemic risks across the world and in the UK. Even if each were a low probability event, the likelihood is high that in an arbitrary time period, *something* will happen - even if the *something* is unpredictable - that will create a systemic risk with profound impacts, easily reaching the hundreds of millions in damages or affected millions of people; hence a high magnitude score has been given for the current and future risk in all scenarios. COVID-19 as an example of a systemic risk is estimated to cost the UK £280bn in 2020 (BBC News, 2020).

## 7.11.2 Extent to which current adaptation will manage the risk (ID10)

### 7.11.2.1 Effects of current adaptation policy and commitments on current and future risk (ID10)

There is clearly significant policy planning across the UK Government for known high-impact, low probability, events (e.g., disaster risk management, or pandemic preparedness). However, such planning typically takes as its focus the ‘black swan’ – a single low probability, high-impact, event (Willis Towers Watson 2020, Kay and King 2020). Systemic risks however can perhaps more commonly arise from a higher-probability, lower-impact events (or multiple events together) that interact with human systems that are already under pressure from other drivers, with the impacts rippling out, and being socially amplified, across sectors, geographies and time. Current adaptation largely considers risks primarily as hazards and treats domains separately and independently.

### 7.11.2.2 Shortfall in current adaptation (ID10)

Systemic risk is rarely a focus of adaptation-planning or planning broader economy (an example is that trade discussions do not consider the extent to which an agreement would increase UK supply chain resilience). Leaving the EU has made it necessary to consider the impacts of severe supply chain/border disruption (Operation Yellowhammer). The experience COVID-19 is also providing more lessons on systemic risks and their impacts.

The take-home message from this chapter is that (a) disruptive events - climate hazards - are made more likely by trends in emissions, driving climate change, and trends in the socio-political and economic factors that affect the exposure and vulnerability to these hazards, and (b) systemic risks are more likely in the future than the past, and potentially more disruptive because all elements of the risk (hazard x exposure x vulnerability) are currently increasing, as discussed in the introduction. Current adaptation largely considers risks primarily in terms of a focus on single hazards, and also largely treats domains separately and independently: systemic risk is rarely a focus of adaptation planning or planning across the broader economy.

Our view is that adaptation should therefore be enacted by integrating knowledge and consideration of climate change’s role in systemic risks into decision-making across government sectors. This may require recognition that systemic risks can arise from one sector and transfer across sectors, and that adaptation planning requires ‘whole of government’ involvement, rather than being led by a single department associated with a given sector. For example, when building new trade relations there is a need to consider systemic resilience as well as its benefit to UK economic growth. In short, there is a need for greater consideration of ensuring that the UK economy adapts to increasing systemic risks arising from the transmission of goods, people, finance, and information from overseas.

## 7.11.2.3 Adaptation Scores (ID10)

<b>Table 7.32</b> Adaptation scores for systematic risk arising from the amplification of named risks cascading across sectors and borders	
<b>Are the risks going to be managed in the future?</b>	
<b>UK</b>	No  (Low confidence)

An adaptation score of ‘no’ reflects the lack of planning across government for these multi-dimensional risks that are increasing through time due to ongoing climate change increasing the hazards, but also a background increase in exposure and vulnerability across the country.

## 7.11.3 Benefits of further adaptation action in the next five years (ID10)

## 7.11.3.1 Indicative costs and benefits of additional adaptation (ID10)

There is an emerging literature on transformational adaptation<sup>9</sup> to deliver better resilience to future climate change. While definitions vary, much of the theoretical literature emphasizes transformational adaptation involving a system-level (systemic) approach and there is often a focus on changes in governance as well as underlying causes of risk or vulnerability (Lonsdale *et al.*, 2015). However, there is very little economic evidence on the costs and benefits of transformational adaptation, reflecting that there is very little concrete evidence on what transformational adaptation looks like in practice (see Watkiss *et al.*, 2020). This is an area where further investigation (of economic evidence) is needed.

## 7.11.3.2 Overall Urgency Score (ID10)

<b>Table 7.33</b> Urgency score for systematic risk arising from the amplification of named risks cascading across sectors and borders	
<b>Urgency Score</b>	More action needed
<b>Confidence</b>	Medium

Due to the systemic nature of international climate risks to the UK - its unpredictability and interconnectedness - adaptation would benefit from increasing the country’s broad resilience to systemic disruptions rather than solely focussing on reducing the exposure of the UK to any one specific risk event and outcome. Therefore, the main adaptation benefits will come from reducing the fragility of our systems, and these will often create co-benefits outside of the reduction of

<sup>9</sup> Defined in this CCRA3 Technical Report as ‘Adaptation that changes the fundamental attributes of a system in anticipation of climate change and its effects’

climate risk. COVID-19 has brought to the fore the notion that economies must consider resilience (OECD 2020b; UNFCCC 2020; Foreign and Commonwealth Office and Lord Ahmad of Wimbledon 2020) as well as ‘productivity’ and ‘growth’ in adapting to the future. OECD 2020a firmly recognises the need to consider systemic risks more deeply than before.

Resilient economies are ones that can absorb shocks or recover quickly: this is often associated with diversity and redundancy (e.g., de-centralised systems, multiple logistical routes, stores/savings/safety nets etc). Many such resilience-building routes have, however, been removed because resilience is less efficient (in times without risk). Given the opportunities of the next decade, as the UK adjusts to leaving the EU and recovers from COVID-19, there is an opportunity to ‘build back better’, where part of the ‘better’ is greater resilience (OECD 2020c). Resilience can also arise from changing behaviour. There are multiple examples where local and regional management that engages with public behaviour is key to developing broad resilience. Examples include:

- From ID9- local surveillance of pathogens in vets and communities and developing behaviour in those communities that reduces risks e.g., plants and water bodies for mosquitos, or an example from behaviour and spread of COVID.
- For ID4- management of conflict risk being more effective when at regional or local level.
- For ID1 and ID2, localizing food systems may be win-win in terms of more sustainable healthy diets but also decreasing vulnerability/exposure to impact of climate risks to food supply, markets and trade.

#### 7.11.4 Looking ahead (ID10)

Systemic risks are likely to increase in the future unless significant adaptation occurs to consider how to build economic resilience to risks cascading from overseas. There are many tools to increase resilience: build more functional redundancy through diversity, distributed networks, substitutability, safety nets, as well as building more resilient societies that can absorb shocks through behavioural change.

## 7.12 References

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