

Scotland's Rural College

National environment and assets

Berry, Pam ; Brown, Iain; Contributing authors; Additional Contributors

Published in:

The Third UK Climate Change Risk Assessment Technical Report

Print publication: 01/01/2021

Document Version

Publisher's PDF, also known as Version of record

[Link to publication](#)

Citation for published version (APA):

Berry, P., Brown, I., Contributing authors, & Additional Contributors (2021). National environment and assets. In R. A. Betts, A. B. Haward, & K. V. Pearson (Eds.), *The Third UK Climate Change Risk Assessment Technical Report* Prepared for the Climate Change Committee. <https://www.ukclimaterisk.org/independent-assessment-ccra3/technical-report/>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

UK Climate Risk
Independent
Assessment (CCRA3)

Technical Report
Chapter 3:
Natural
Environment and
Assets

Lead Authors: Pam Berry, Iain Brown

Contributing Authors: Richard Betts, Pete Falloon, Debbie Hemming, Mike Morecroft, Stephen Thackeray, Kairsty Topp, Paul Watkiss

Additional Contributors: Brendan Freeman, Kathryn Brown, Amy Bell, Jade Berman, Alistair Hunt, Jane McCullough, Alan Netherwood, Catherine Payne, Rob Knowles

This chapter should be cited as:

Berry, P. and Brown, I. (2021) National environment and assets. In: *The Third UK Climate Change Risk Assessment Technical Report* [Betts, R.A., Haward, A.B. and Pearson, K.V. (eds.)]. Prepared for the Climate Change Committee, London

Contents

Key messages.....	5
3.1 Introduction.....	10
3.1.1 Context and scope of chapter.....	11
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).....	19
3.2.1 Current and future level of risk (N1).....	20
3.2.2 Extent to which current adaptation will manage the risk (N1).....	36
3.2.3 Benefits of further adaptation action in the next five years (N1).....	43
3.2.4 Looking ahead (N1).....	44
3.3 Risks to terrestrial species and habitats from pests and pathogens, including Invasive Non-Native Species (N2).....	45
3.3.1. Current and future level of risk (N2).....	46
3.3.2. Extent to which current adaptation will manage the risk or opportunity (N2).....	53
3.3.3 Benefits of further adaptation action in the next five years (N2).....	58
3.3.4. Looking ahead (N2).....	59
3.4. Opportunities from new species in terrestrial habitats colonisations (N3).....	60
3.4.1 Current and future level of opportunity (N3).....	61
3.4.2. Extent to which current adaptation will manage the opportunity (N3).....	66
3.4.3 Benefits of further adaptation action in the next five years (N3).....	68
3.4.4 Looking ahead (N3).....	69
3.5. Risks to soils from changing climatic conditions, including seasonal aridity and wetness (N4).....	69
3.5.1 Current and future level of risk (N4).....	70
3.5.2 Extent to which current adaptation will manage the risk (N4).....	80
3.5.3 Benefits of further adaptation action in the next five years (N4).....	85
3.5.4 Looking ahead (N4).....	88
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).....	89
3.6.1 Current and future level of risk and opportunity (N5).....	90
3.6.2 Extent to which current adaptation will manage the risk and opportunity (N5).....	100
3.6.3 Benefits of further adaptation action in the next five years (N5).....	106
3.6.4 Looking ahead (N5).....	108

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)	108
3.7.1 Current and future level of risk and opportunity (N6)	110
3.7.2 Extent to which current adaptation will manage the risk and opportunity (N6)	135
3.7.3 Benefits of further adaptation action in the next five years (N6)	145
3.7.4 Looking ahead (N6)	153
3.8. Risks to agriculture from pests, pathogens, and INNS (N7)	153
3.8.1 Current and future level of risk (N7)	155
3.8.2 Extent to which current adaptation will manage the risk (N7)	164
3.8.3 Benefits of further adaptation action in the next five years (N7)	169
3.8.4 Looking ahead (N7)	172
3.9. Risks to forestry from pests, pathogens, and INNS (N8)	172
3.9.1 Current and future level of risk (N8)	173
3.9.2 Extent to which current adaptation will manage the risk (N8)	179
3.9.3 Benefits of further adaptation action in the next five years (N8)	183
3.9.4 Looking ahead (N8)	185
3.10. Opportunities for agricultural and forestry productivity from new/alternative species becoming suitable (N9)	185
3.10.1 Current and future level of opportunity (N9)	186
3.10.2 Extent to which current adaptation will manage the opportunity (N9)	192
3.10.3 Benefits of further adaptation action in the next five years (N9)	195
3.10.4 Looking ahead (N9)	196
3.11. Risks to aquifers and agricultural land from saltwater intrusion (N10)	197
3.11.1 Current and future level of risk (N10)	198
3.11.2 Extent to which current adaptation will manage the risk (N10)	202
3.11.3 Benefits of further adaptation action in the next five years (N10)	204
3.11.4 Looking ahead (N10)	205
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)	206
3.12.1 Current and future level of risk (N11)	207
3.12.2 Extent to which current adaptation will manage the risk (N11)	224
3.12.3 Benefits of further adaptation action in the next five years (N11)	231
3.12.4 Looking ahead (N11)	232

3.13. Risks to freshwater species and habitats from pests, pathogens and invasive species (N12)	233
3.13.1 Current and future level of risk (N12)	234
3.13.2 Extent to which current adaptation will manage the risk (N12)	240
3.13.3 Benefits of further adaptation action in the next five years (N12)	243
3.13.4 Looking ahead (N12)	244
3.14. Opportunities to freshwater species and habitats from new species colonisations (N13)	244
3.14.1 Current and future level of opportunity (N13)	245
3.14.2 Extent to which current adaptation will manage the opportunity (N13)	248
3.14.3 Benefits of further adaptation action in the next five years (N13)	249
3.14.4 Looking ahead (N13)	250
3.15. Risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures. (N14)	250
3.15.1 Current and future level of risk (N14)	252
3.15.2 Extent to which current adaptation will manage the risk (N14)	265
3.15.3 Benefits of further adaptation action in the next five years(N14)	272
3.15.4 Looking ahead (N14)	274
3.16. Opportunities to marine species, habitats and fisheries from changing climatic conditions (N15)	275
3.16.1 Current and future level of opportunity (N15)	276
3.16.2 The extent to which current adaptation will manage the opportunity (N15)	279
3.16.3 Benefits of further adaptation action in the next five years (N15)	281
3.16.4 Looking ahead (N15)	282
3.17. Risks to marine species and habitats from pests, pathogens and invasive species (N16)	282
3.17.1 Current and future level of risk (N16)	283
3.17.2 Extent to which current adaptation will manage the risk (N16)	290
3.17.3 Benefits of further adaptation action in the next five years (N16)	293
3.17.4 Looking ahead (N16)	295
3.18 Risks and opportunities to coastal species and habitats due to coastal flooding, erosion, and climate factors (Risk N17)	295
3.18.1 Current and future level of risk or opportunity (N17)	297
3.18.2 Extent to which the current adaptation will manage the risk (N17)	311
3.18.3 Benefits of further adaptation action in the next five years (N17)	327
3.18.4 Looking ahead (N17)	332
3.19 Risks and opportunities from climate change to landscape character (Risk N18)	333

3.19.1 Current and future level of risk and opportunity (N18)	335
3.19.2 Extent to which current adaptation will manage the risk and opportunity (N18)	340
3.19.3 Benefits of further adaptation action in the next five years	345
3.19.4 Looking ahead (N18)	346
3.20 Cross-cutting Risks (including with other CCRA Chapters)	346
3.20.1 Synergies and trade-offs between Net Zero and adaptation for the natural environment	347
3.20.2 Ecosystem Services and the Role of Nature-based Solutions	349
3.20.3 Implications for Key Ecosystem Service Relationships	352
3.20.4 Progress on Adaptation for Key Ecosystem Service Relationships	356
3.21. References	359

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

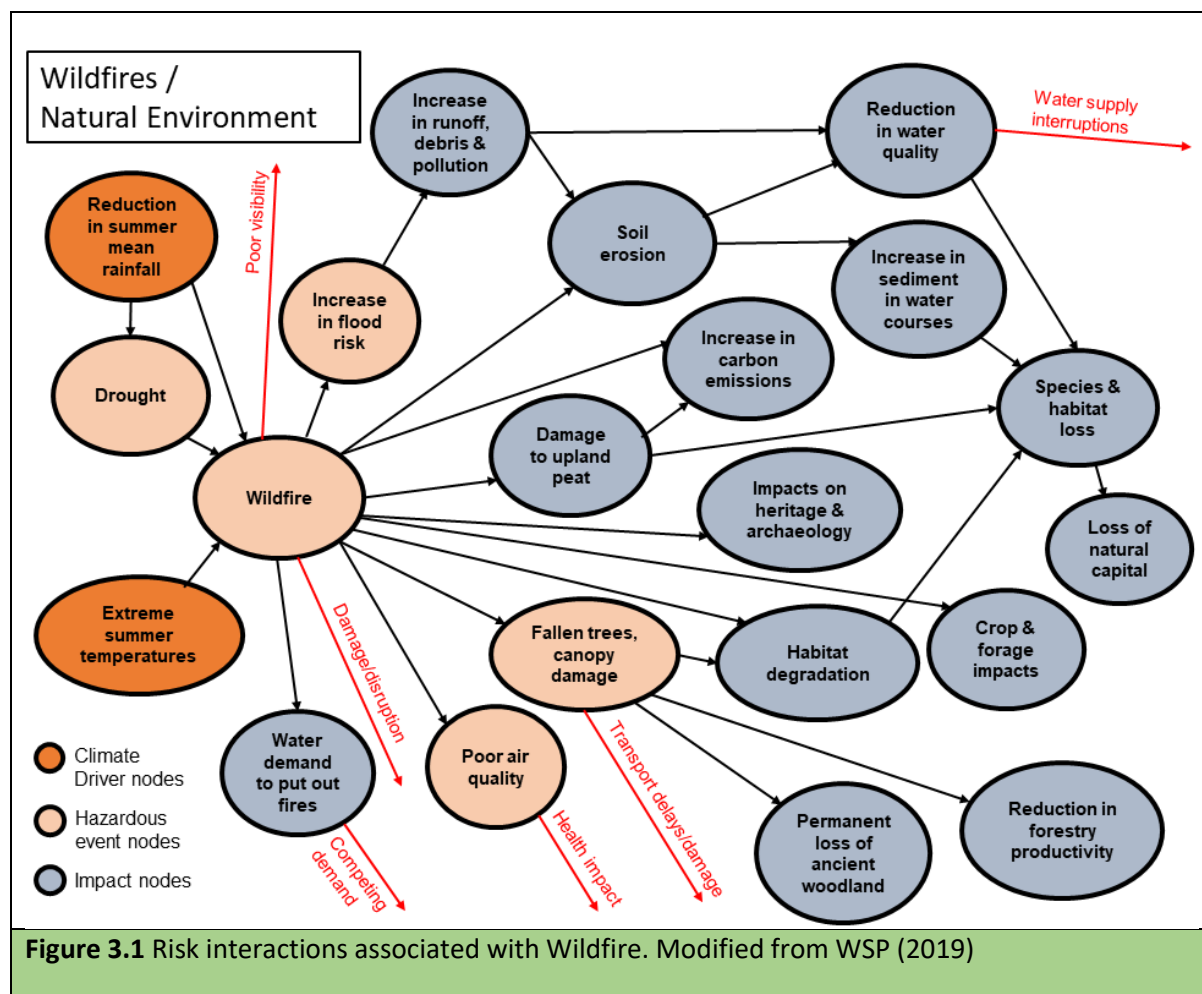
There is a variable, but increasing, amount of evidence available for the assessment of the magnitude of each risk descriptor, as the chapter is based on new evidence since CCRA2, although there is less available for the opportunities. The amount available has, to a large extent, been dependent on the 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 Vanvye, 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 Vanvye, 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⁻¹, 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.

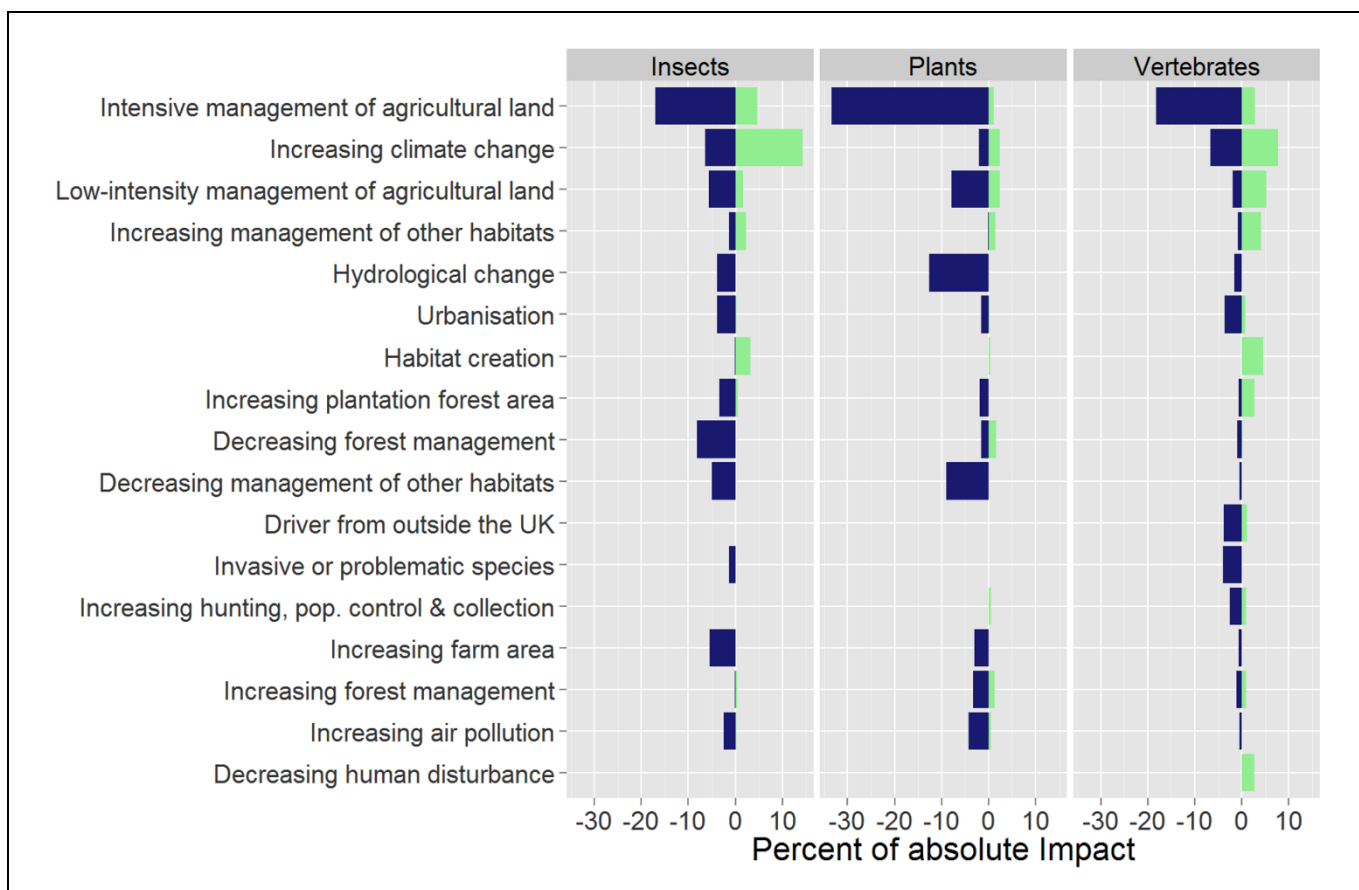


Figure 3.2 Changes in populations of different species and drivers (Reproduced from Burns *et al.*, 2016). Absolute positive impact is the sum of all the positive weighted Strength of Impact scores allocated to that driver; negative absolute impact is the sum of all the negative weighted Strength of Impact scores allocated to that driver). These were expressed as a percentage of the total across all drivers of change.

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 2100¹ 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).

¹ UKCP09 medium scenario (SRES A1B)

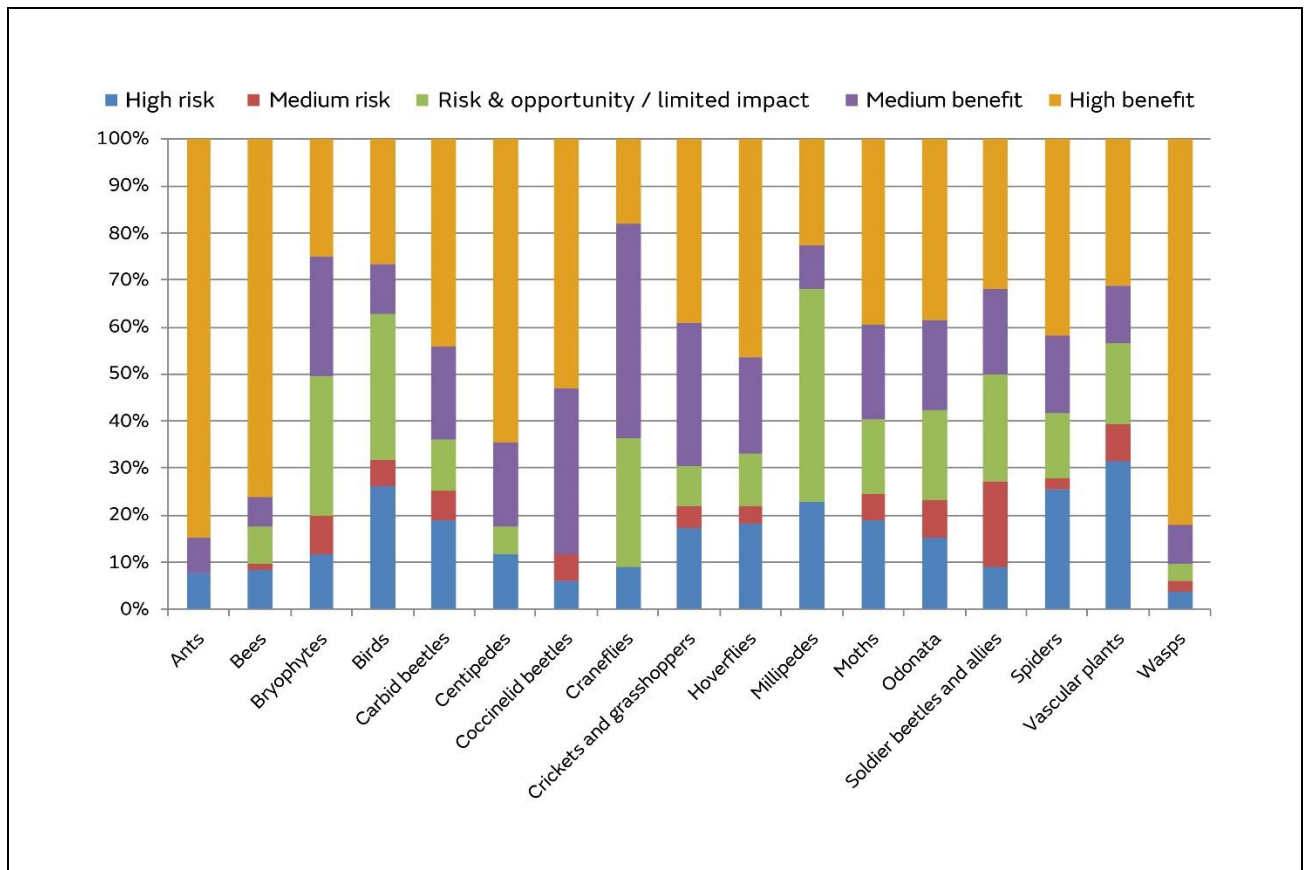
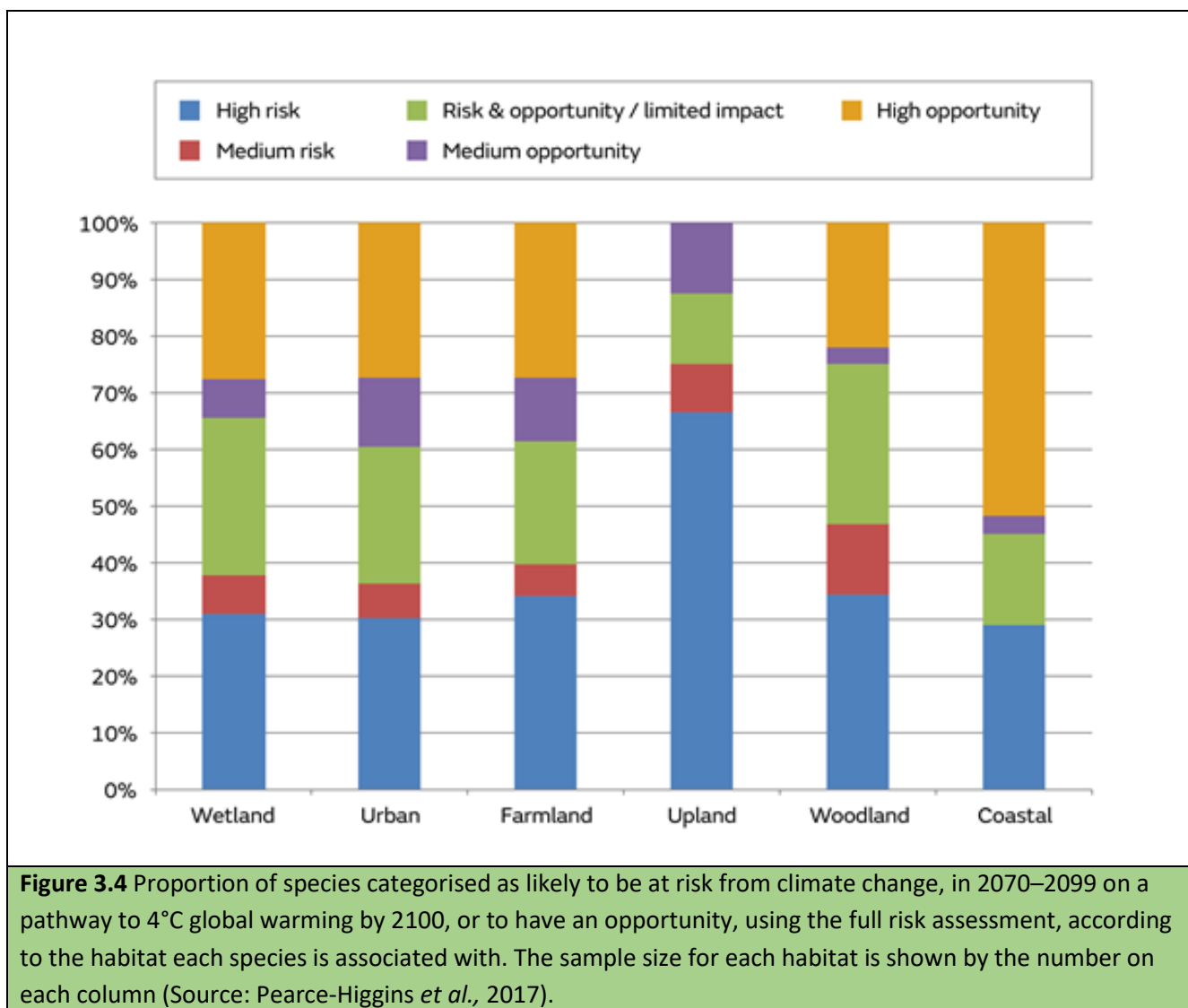


Figure 3.3 Proportion of species categorised as likely to be at risk or to have an opportunity for expansion from climate change in 2070–2099 on a pathway to 4°C global warming by 2100, in different taxonomic groups, as assessed by the simplified risk assessment. Source: Pearce-Higgins *et al.* (2017).



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 2100², 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).

² UKCP09 spatially-coherent projections with the A1B scenario

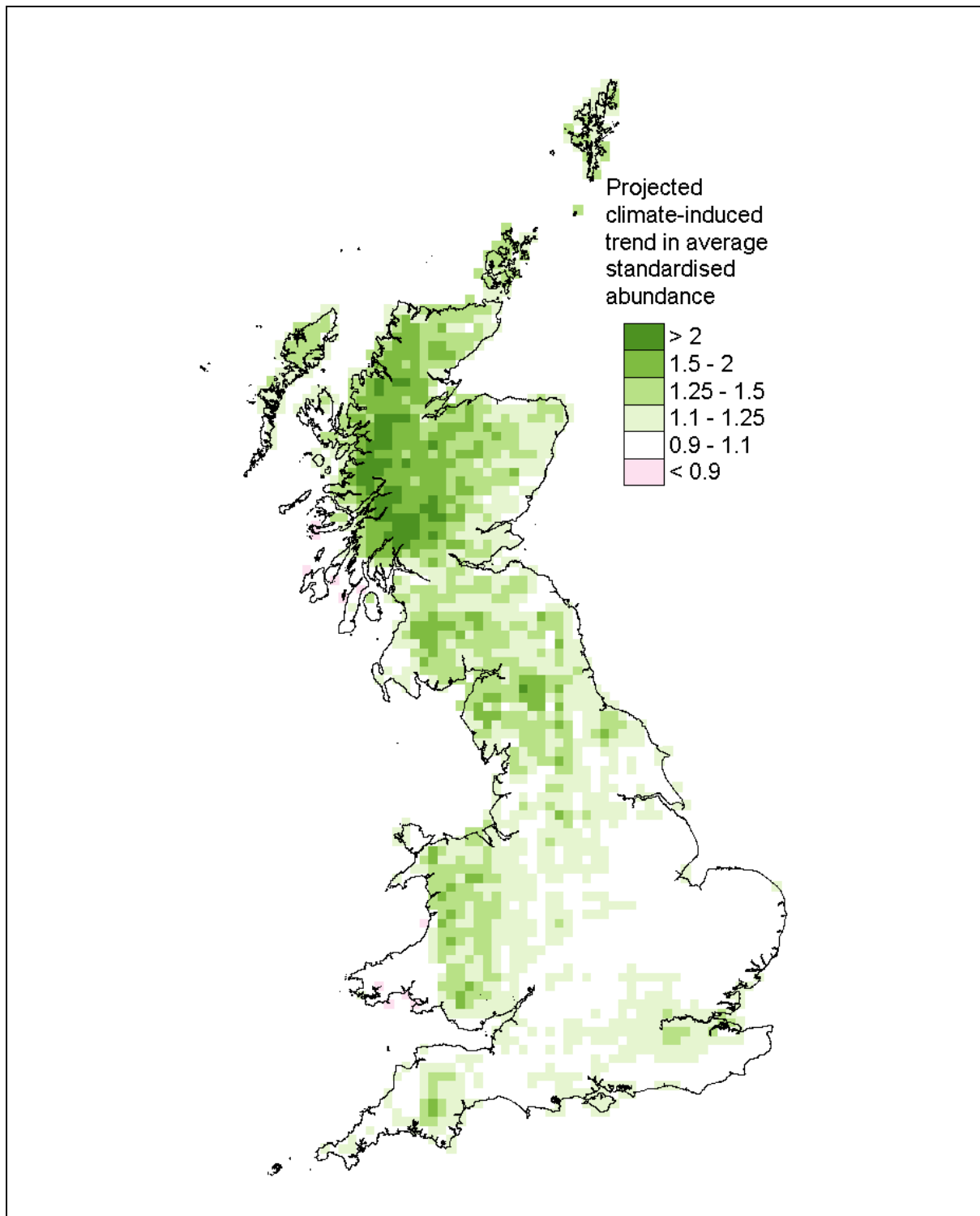


Figure 3.5 Projected climate-induced gains and losses in bird species abundance by 2080 on a pathway to approximately 4°C global warming by 2100. The trend is the ratio between future and current average normalised abundance across species. The average standardised abundance is the ratio between the average normalised abundance across species projected for 2050 or 2080 and the present average normalised abundance. Abundance was normalised by dividing all estimates for a species by the maximum projected abundance, across all years and scenarios. Reproduced from Massimino *et al.* (2017).

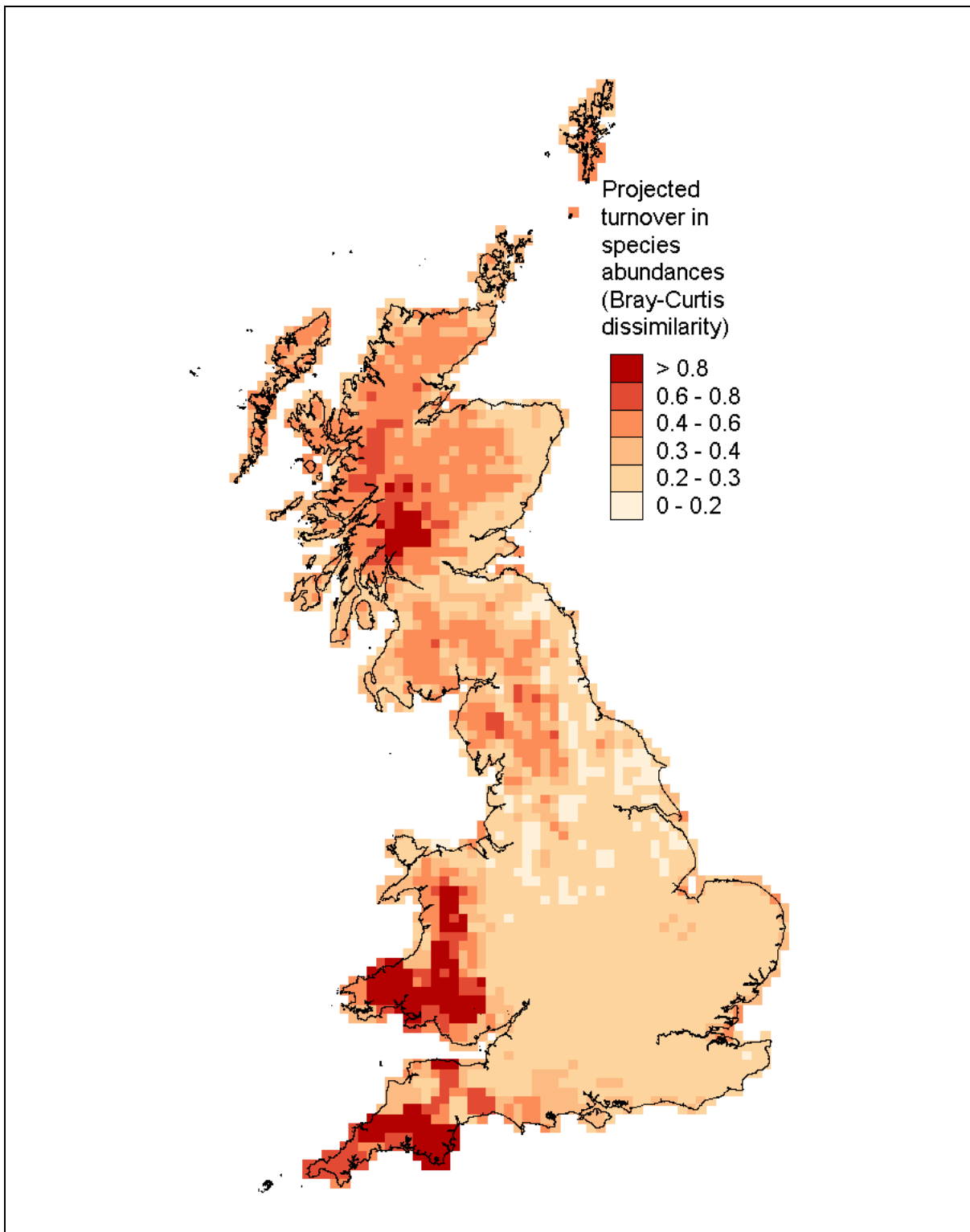
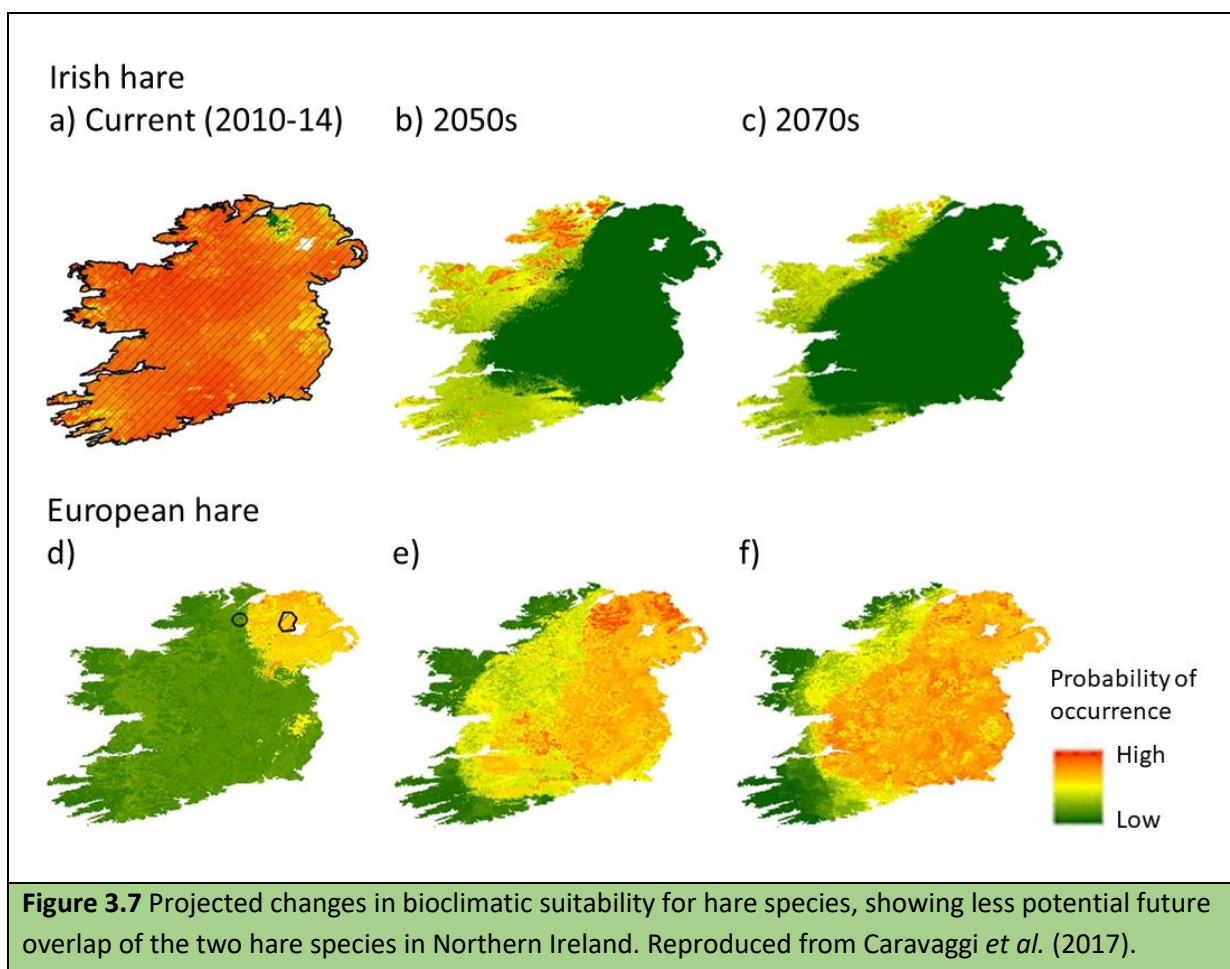


Figure 3.6 Projected climate-induced turnover in bird species abundance by 2080 on a pathway to approximately 4°C global warming by 2100. Turnover is calculated as the Bray–Curtis dissimilarity between the current and future projected abundance, where 0 means the species composition of the grid square is exactly the same in the two periods, and 1 means the two periods do not share any species. Reproduced from Massimino *et al.* (2017).

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 projections³ 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

³ 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 associate 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 CO₂ 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 trees 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)

Table 3.2 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).					
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 (High confidence)	High (Medium confidence)	High (Medium confidence)	High (medium confidence)	High (Medium confidence)
Northern Ireland	High (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Scotland	High (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Wales	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)

Table 3.3 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)			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
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 14th 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.forestryresearch.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.forestryresearch.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 (29th 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.

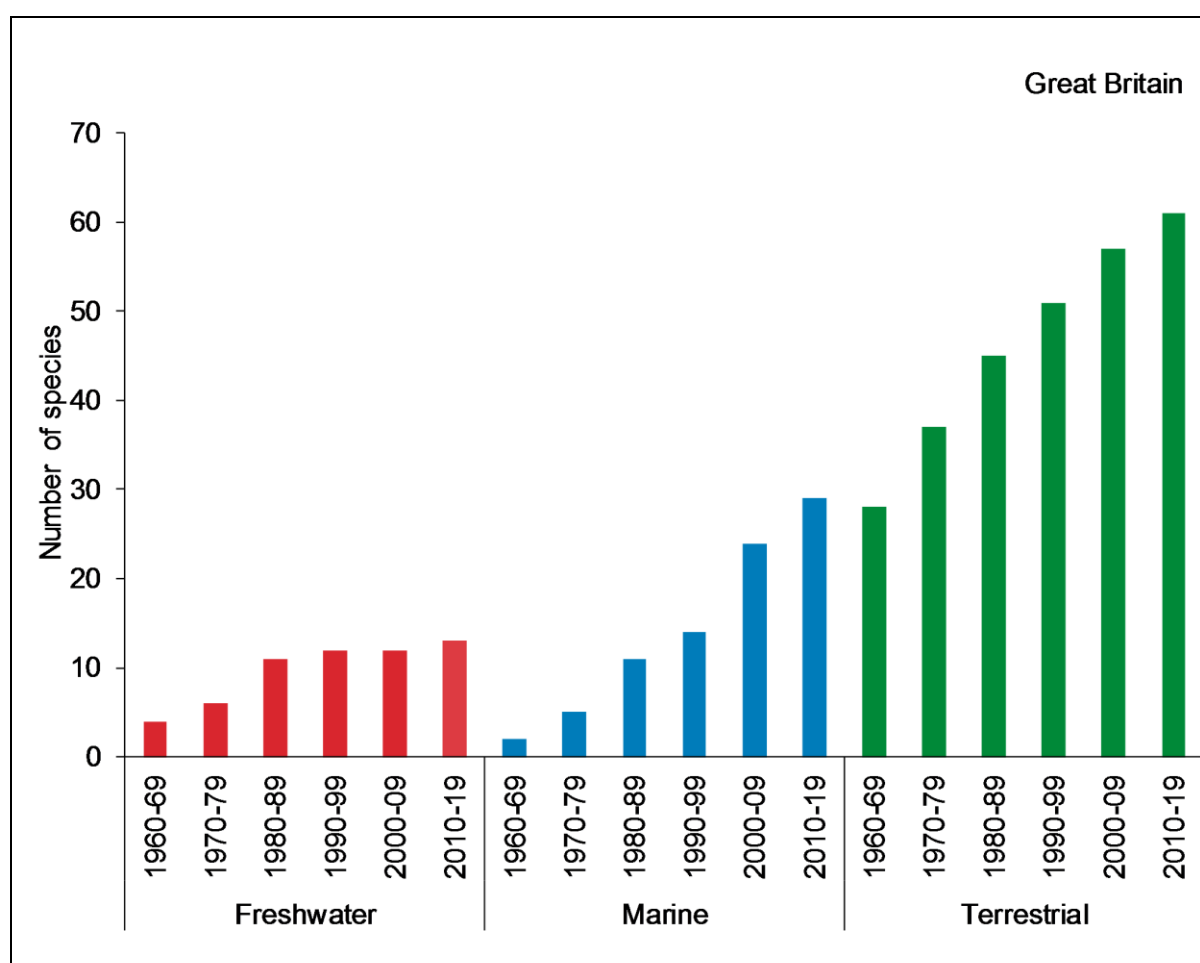


Figure 3.8. Number of invasive non-native species established across or along 10% or more of the land area or coastline of Great Britain, 1960 to 2018. **Notes:** The last time period is shorter than the other bars (from 2010 to 2018). Source: Botanical Society of Britain & Ireland, British Trust for Ornithology, Centre for Ecology & Hydrology, Marine Biological Association, National Biodiversity Network. Reproduced from Harrower *et al.*, (2019).

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 warming⁴ 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).

⁴ 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 century⁵, 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).

⁵ 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
England	Medium (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Northern Ireland	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
Scotland	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
Wales	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). 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)

Table 3.6 Adaptation scores for risks to terrestrial species and habitats from pests and pathogens, including Invasive Non-Native Species			
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)

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)

Table 3.7 Urgency scores for risks to terrestrial species and habitats from pests and pathogens, including Invasive Non-Native Species.				
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

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 2100⁶, 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 2100⁷) 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

⁶ UKCP09 probabilistic projections with the low (SRES B1) scenario

⁷ 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)

Table 3.8 Magnitude scores for opportunities from new species in terrestrial habitats colonisations .					
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 confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
Northern Ireland	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
Scotland	Medium (High confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
Wales	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)

Table 3.9 Opportunities from new species in terrestrial habitats colonisations			
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)

3.4.3 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)

Table 3.10 Urgency scores for opportunities from new species in terrestrial habitats colonisations				
Country	England	Northern Ireland	Scotland	Wales
Urgency Score	Further investigation	Further investigation	Further investigation	Further investigation
Confidence	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 CO₂) 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 N₂O 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 soilscares 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 MtCO₂e/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 soilscares 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: Jaroszowski, 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 2041-2070⁸ 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 century⁹ (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.

⁸ EuroCORDEX regional climate model ensemble with both the RCP4.5 and RCP8.5 concentrations pathways

⁹ 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 century¹⁰ 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

¹⁰ 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 CO₂ 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 warming¹¹, 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

¹¹ 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 a 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)

Table 3.11 Magnitude scores for risks to soils from changing climatic conditions, including seasonal aridity and wetness					
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 confidence)	High (Low confidence)	High (Low confidence)	High (low confidence)	High (Low confidence)
Northern Ireland	Medium (Low confidence)	High (Low confidence)	High (Low confidence)	High (low confidence)	High (Low confidence)
Scotland	Medium (medium) confidence)	High (Low confidence)	High (Low confidence)	High (low confidence)	High (Low confidence)
Wales	Medium (Medium confidence)	High (Low confidence)	High (Low confidence)	High (low confidence)	High (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 (4th 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)

Table 3.12 Adaptation scores for risks to soils from changing climatic conditions, including seasonal aridity and wetness			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
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)

Table 3.13 Urgency scores for risks to soils from changing climatic conditions, including seasonal aridity and wetness				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	More action needed	More action needed	More action needed
Confidence	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 CO₂ this assessment also includes the two other biogenic GHGs associated with the natural environment, CH₄ and N₂O, 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 CO₂ 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 CO₂ or CH₄ depending on presence of aerobic or anaerobic conditions (i.e., soil wetness) and temperature. In addition, N₂O 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 CH₄ emissions from ruminant livestock and N₂O 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 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, 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 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 MtCO₂e 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 CO₂ ranging between 1.07 (0.07–4.69) kg s⁻¹ and 13.7 (1.73–50.1) kg s⁻¹, 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 CO₂). 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 CO₂. 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/ m²) with other habitats also providing significant opportunities notably seagrass meadows (ca. 20-70gC/ m²) and kelp forests (ca. 30 gC/m²) (e.g., Laffoley and Grimsditch, 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/m². 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 CO₂ 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 CO₂ 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 CO₂, 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 century¹² suggest the combined climate and CO₂ 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.*,

¹² 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 CO₂ emissions, it is very likely that changes will also impact the flux of N₂O, 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 NH₃ due to increased future evapotranspiration rates, and changes in denitrification of aquatic NO₃ in streams due to warming, both of which indirectly contribute to N₂O 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 CCRA, 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 N₂O 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 CO₂ 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 ≥ 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) 6th 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
England	Medium (Medium confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Northern Ireland	Medium (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Scotland	Medium (Medium confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Wales	Medium (Medium confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (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 20,000m² 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 CO₂ emissions, therefore including CH₄ and N₂O 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 (N₂O, NH₃) and water pollution (NO₃) 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 CO₂e (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
Urgency score	More action needed	More action needed	More action needed	More action needed
Confidence	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 20th 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 21st 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 CCRA, 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.

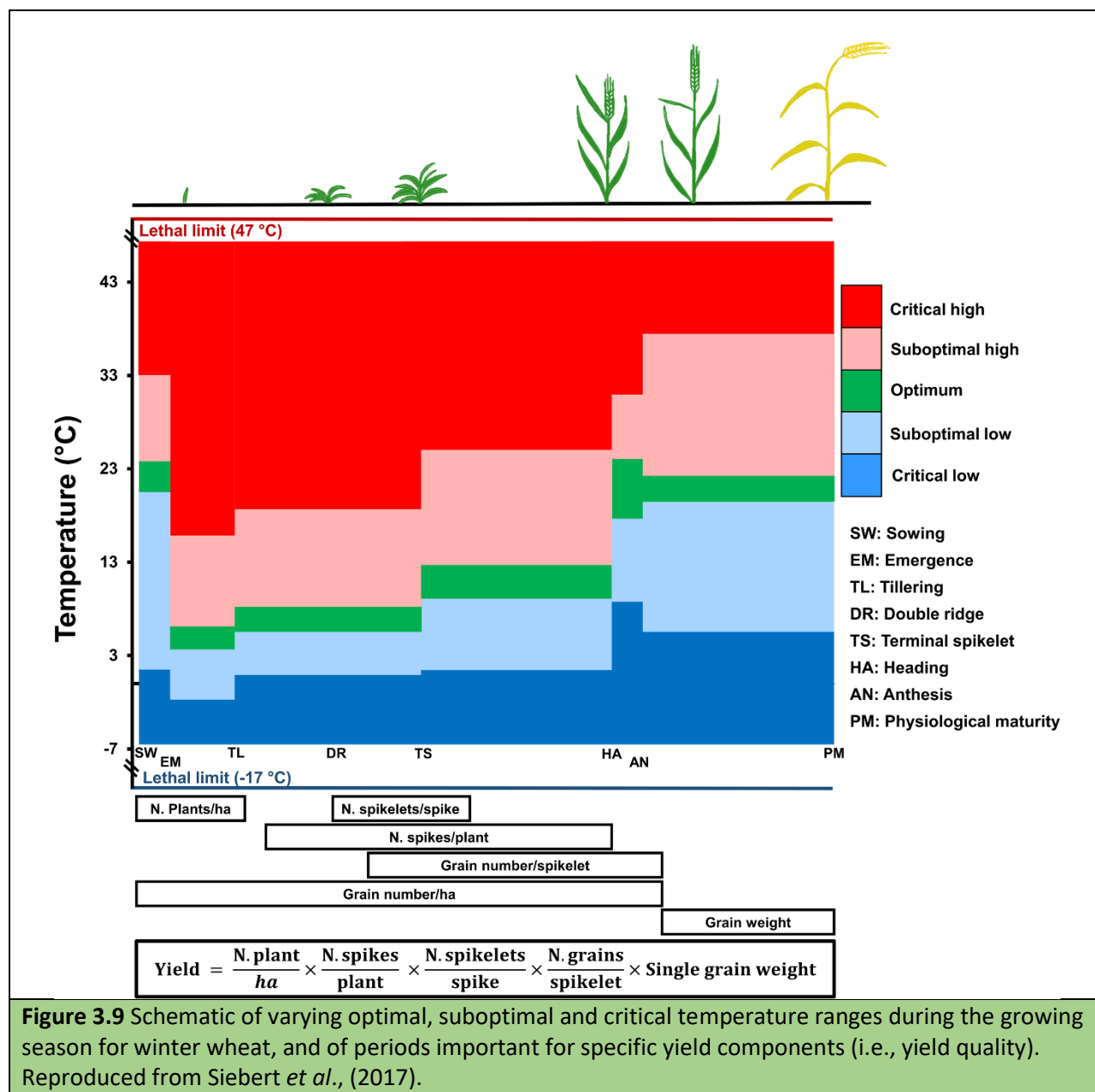
The impact of anomalous weather conditions on agricultural production is also being shown more clearly across Europe. This evidence has relevance to the UK because in some cases the impact of

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 CO₂ 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 CO₂ 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.

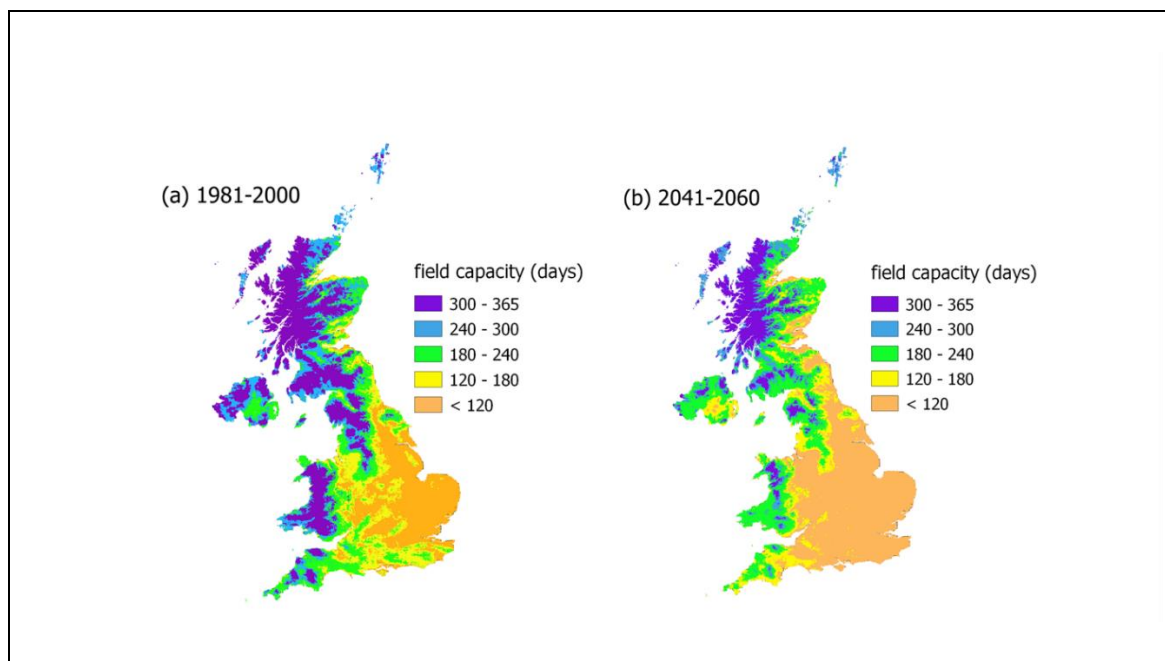


Figure 3.10 Mean UK duration of annual field capacity (days) UK for (i) the baseline period 1981-2000 (ii) 2041-2060 based upon the ensemble mean for UKCP18 spatially coherent projections and RCP8.5 (NB. these reference climate data show the length of the main seasonal period when soils are fully saturated; locally, this period will be further modified by soil drainage properties, including any artificial drainage, and potentially land use characteristics: - updated analysis based upon Brown (2017) using grass as reference land cover).

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 2050¹³ 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 century¹⁴ or 10-25% risk for a model simulating 5°C global warming at the end of the century¹⁵; 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 century¹⁶ 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

¹³ 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

¹⁴ The GISS climate model driven with the RCP8.5 concentrations pathway

¹⁵ The HadGEM2-ES climate model driven with the RCP8.5 concentrations pathway

¹⁶ 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 CO₂ 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 CO₂ 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 CO₂ (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 CO₂ 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 CO₂ 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 CH₄ 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 2060s¹⁷ 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

¹⁷ 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 century¹⁸, 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 CO₂ and atmospheric deposition of N and S pollutants. Large-scale analysis of CO₂ 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)

¹⁸ 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 CO₂ 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 CO₂ 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 (O₃) concentrations). Regarding yield quality, there is some experimental evidence that elevated CO₂ 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 CO₂ 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 (CO₂ and N₂O 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 N₂O 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 CO₂ 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 20th 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
England	Medium (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Northern Ireland	Medium (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Scotland	Medium (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Wales	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 developed 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 m³) compared to surface water (ca. 15 million m³) 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)

Table 3.20 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)			
Are the risks and opportunities going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
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 m³/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 CO₂ 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 century¹⁹, 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.

¹⁹ 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 5th to 95th 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 'sleeper species'), although there still remains very little evidence on this issue. This includes the prospect that pests may becoming 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
England	Medium (High confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Northern Ireland	Medium (High confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Scotland	Medium (High confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Wales	Medium (High confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)	High (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 (GBNNS) coordinate work across England, Wales and Scotland, including a GB-wide strategy (latest version published in 2015) and report card (GBNNS, 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 CCRA 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.

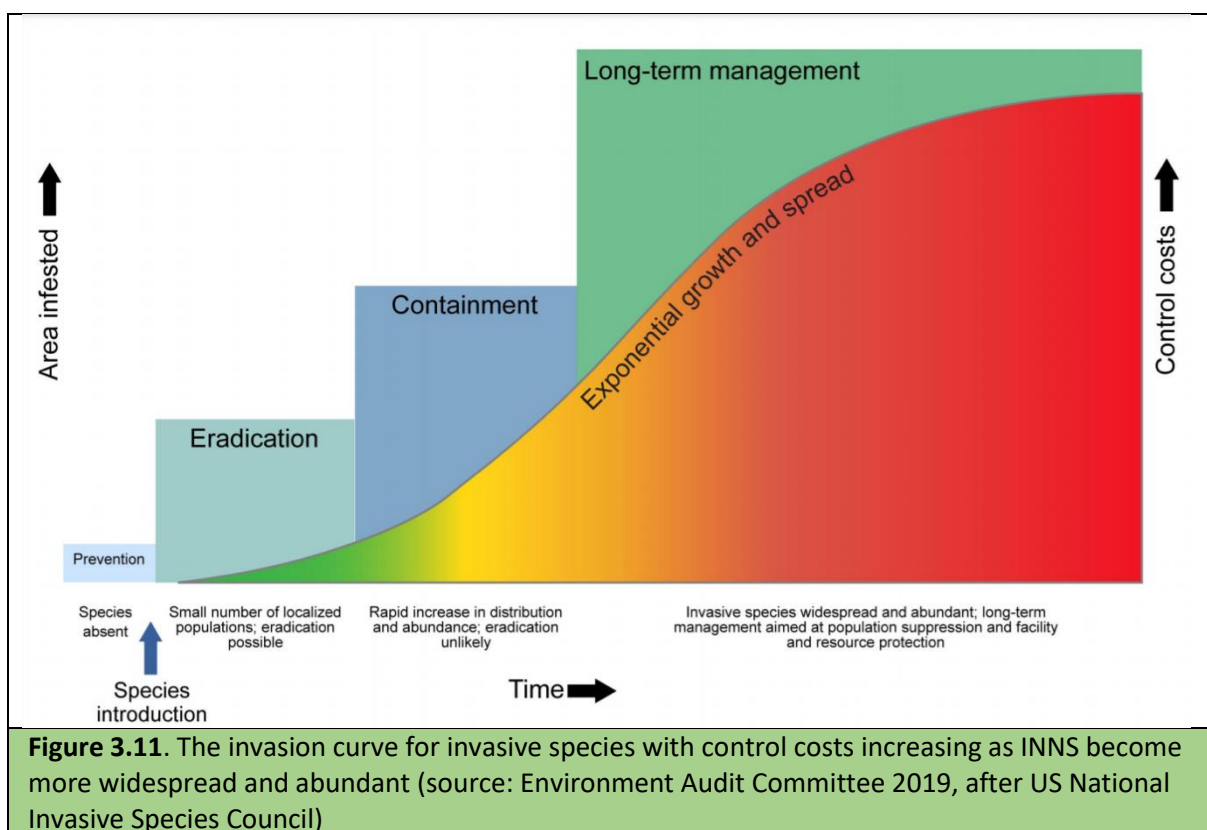
3.8.2.5 Adaptation Scores (N7)

Table 3.24 Adaptation scores for risks to agriculture from pests, pathogens, and INNS			
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)

3.8.3 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 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)

Table 3.25 Urgency scores for risks to agriculture from pests, pathogens, and INNS				
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

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 *Agilus 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 (High confidence)	Med-High (low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Northern Ireland	Medium (High confidence)	Med-High (low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Scotland	Medium (High confidence)	Med-High (low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Wales	Medium (High confidence)	Med-High (low confidence)	High (Low confidence)	High (Low confidence)	High (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 (GBNNS) 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 CCRA 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)

Table 3.27. Adaptation scores risks to forestry from pests, pathogens, and INNS			
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)

3.9.3 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)

Table 3.28 Urgency scores for risks to forestry from pests, pathogens, and INNS				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	More action needed	More action needed	More action needed
Quality of evidence	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 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 N₂O 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 CO₂ 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 century²⁰, 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

²⁰ 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). Viticulture 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 (Low confidence)	Medium-High (low confidence)	High (low confidence)	High (Low confidence)	High (Low confidence)
Northern Ireland	Medium (Low confidence)	Medium-High (low confidence)	High (low confidence)	High (Low confidence)	High (Low confidence)
Scotland	Medium (Low confidence)	Medium-High (low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Wales	Medium (Low confidence)	Medium-High (low confidence)	High (Low confidence)	High (Low confidence)	High (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) 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)

Table 3.30 Opportunities for agricultural and forestry productivity from new/alternative species becoming suitable			
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)

3.10.3 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 coordinated 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)

Table 3.31 Urgency scores for opportunities for agricultural and forestry productivity from new/alternative species becoming suitable				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further Investigation	Further Investigation	Further Investigation	Further investigation
Confidence	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.

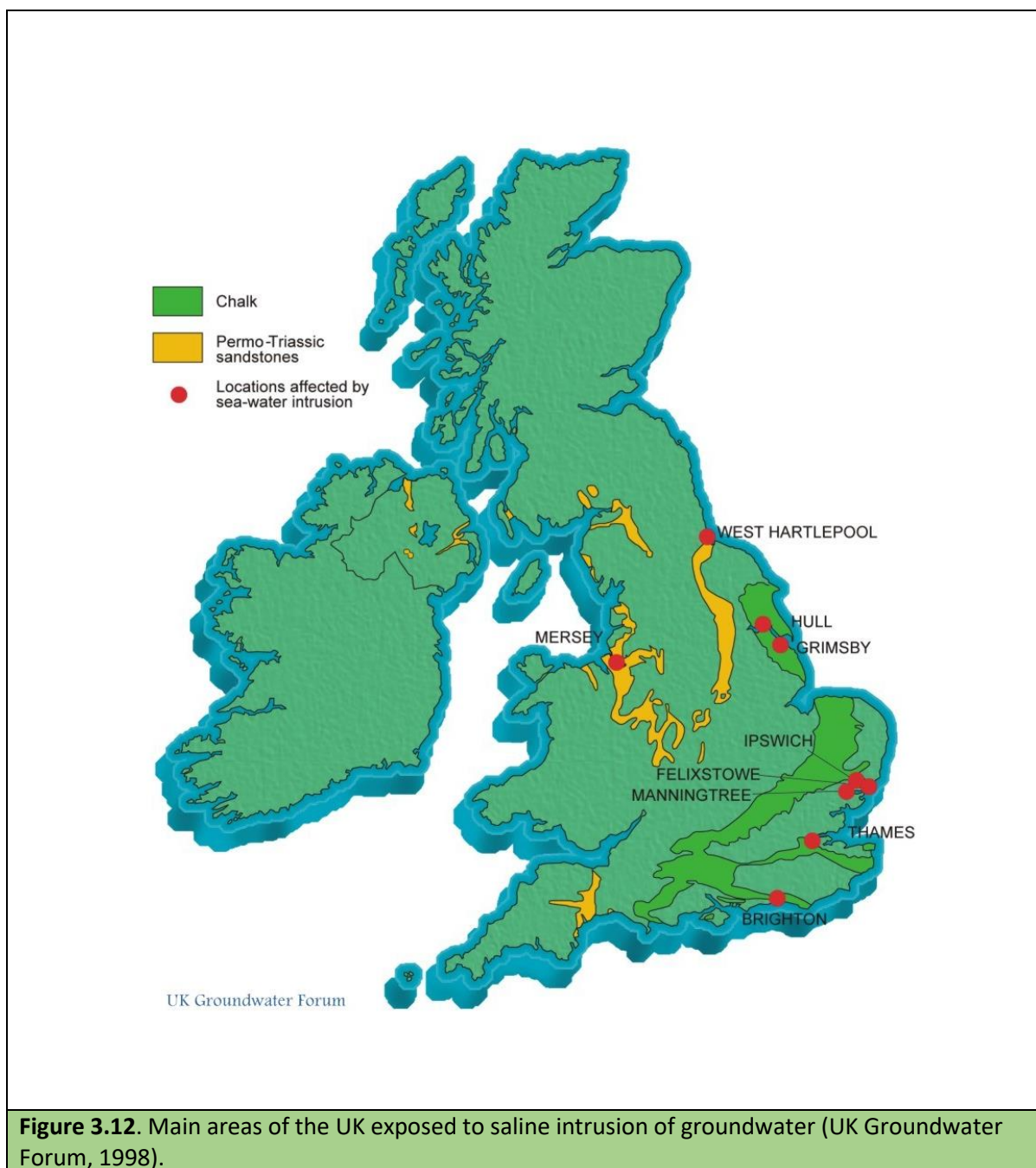


Figure 3.12. Main areas of the UK exposed to saline intrusion of groundwater (UK Groundwater Forum, 1998).

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 MI/d, although the deployable output is lower: up to 15.36 MI/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 century²¹, 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.

²¹ 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
England	Low (High confidence)	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)	Unknown
Northern Ireland	Low (High confidence)	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)
Scotland	Low (High confidence)	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)	Low (Medium confidence)
Wales	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)

Table 3.33 Adaptation scores risks to aquifers and agricultural land from saltwater intrusion			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Yes (Medium confidence)	Yes (Medium confidence)	Yes (Medium confidence)	Yes (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)

Table 3.34 Urgency scores for risks to aquifers and agricultural land from saltwater intrusion				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further Investigation	Watching Brief	Watching Brief	Further Investigation
Confidence	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 warming²². 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.

²² 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⁻¹ for intense rainfall, -1.3 °C h⁻¹ for snow melt, and +1.2 °C h⁻¹ 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)

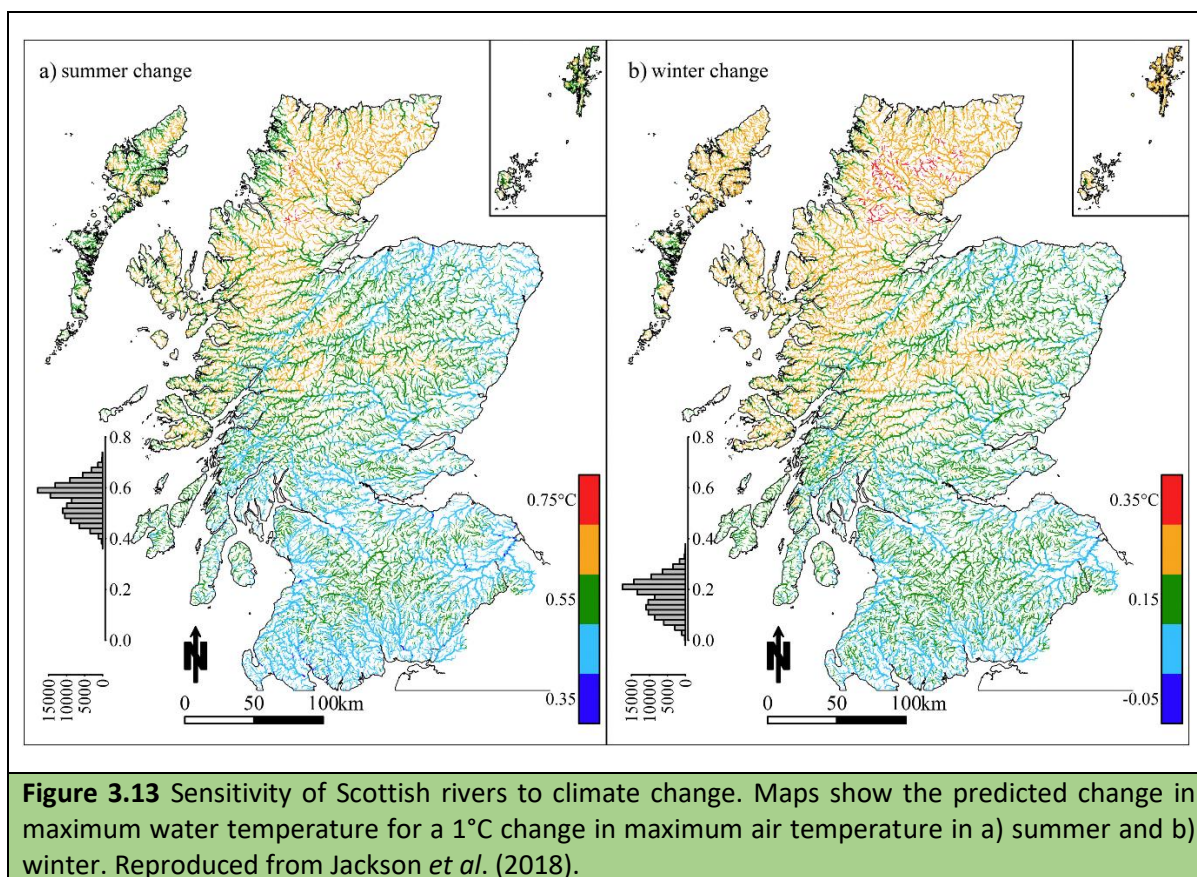
UKCP18 climate scenarios suggest substantial increases in winter daily precipitation, both frequency and intensity, especially in western Britain (Chapter 1: Slingo, 2021). This has implications for river flows, flood risk and water resource management. Similarly, summers are projected to be hotter and 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 2100²³), 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.

²³ 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 century²⁴, 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

²⁴ 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 50th 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 50th 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.

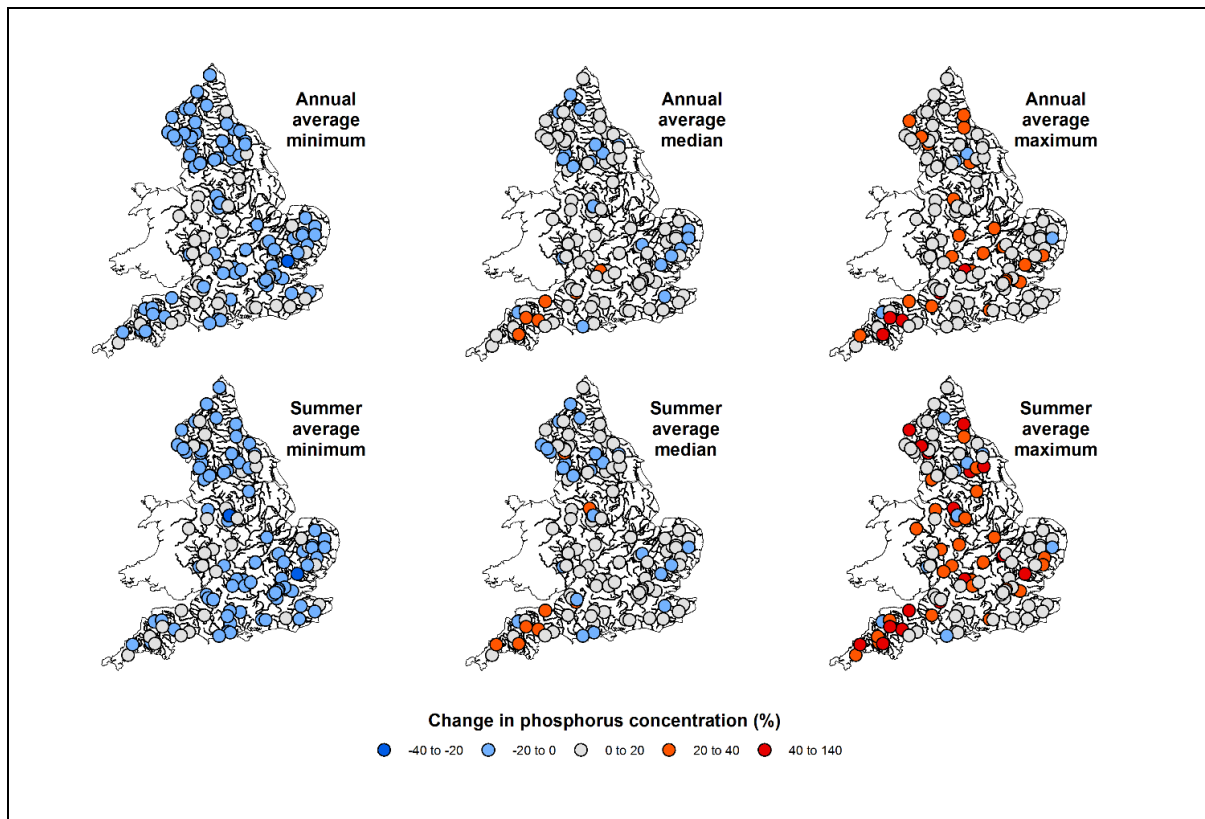


Figure 3.14 Maximum, median, and minimum maps of percentage change in phosphorus concentration from baseline to 2050s for annual average and summer average. Reproduced from Charlton *et al.* (2018).

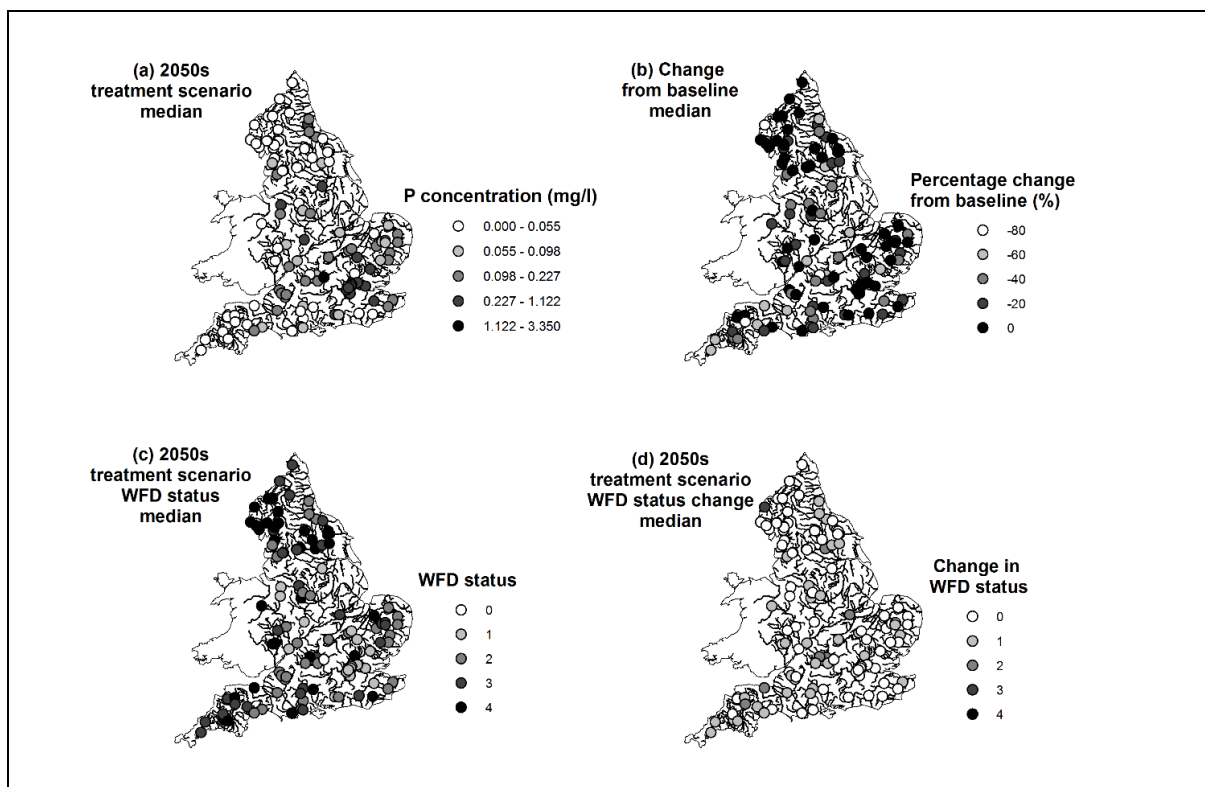


Figure 3.15 Median annual average under treatment scenario: (a) absolute 2050s P concentration (mg/L). (b) percentage change between 2050s and baseline. (c) 2050s WFD status. (d) Change in WFD status. Reproduced from Charlton *et al.* (2018).

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 century²⁵, 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 century²⁶ 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

²⁵ UKCP09 HadRM3 regional climate model perturbed-parameter ensemble with the SRES A1B scenario

²⁶ 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 CO₂ 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	Yellow	Blue		Yellow
Acid and nitrogen deposition	Yellow	Blue	Blue	Yellow
Un-ionised ammonia	Yellow	Blue		Yellow
Nitrate in drinking water	Yellow			Yellow
Microbiological contamination	Yellow	Blue		Yellow
Sediments	Yellow		Blue	Yellow
Chemical pollution	Yellow	Blue	Blue	Yellow
Hydromorphological alterations	Yellow	Yellow	Blue	Yellow
Water quantity	Yellow	Blue	Blue	Yellow
INNS	Yellow			Yellow

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 m³ s⁻¹, >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
England	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
Northern Ireland	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)
Scotland	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	High (Medium confidence)
Wales	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 NO₃/l. At 51 of the 54 groundwater monitoring stations (94%) in 2018, groundwater nitrate concentrations were consistently below 25 mg NO₃/l. The Groundwater Daughter Directive (2006/118/EC) sets the groundwater quality standard at 50 mg NO₃/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 Statement²⁷ 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.

²⁷ <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 Portal²⁸). 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.

²⁸ <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 warming²⁹ 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

²⁹ 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).

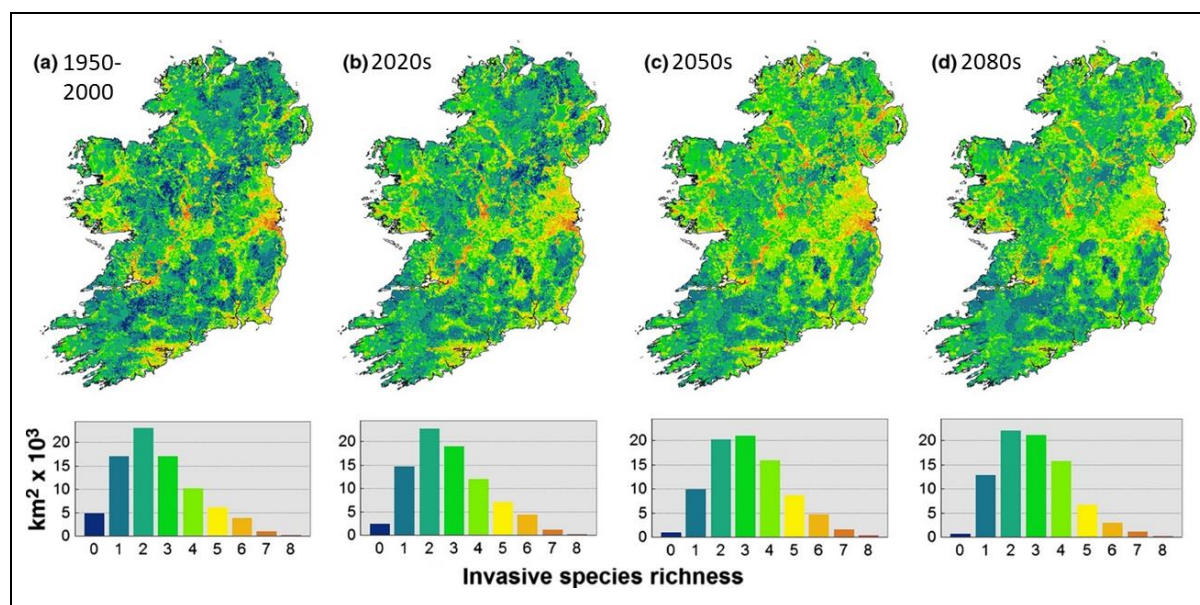


Figure 3.16 Temporal changes in ‘hot- and coldspots’ of invasions in Ireland. Maps show the numbers of invasive species, shown by colours as defined in the histograms below, for (a) baseline conditions using 1950-2000 observed data, and projected climates for the (b) 2020s, (c) 2050s, and (d) 2080s, for a scenario of approximately 4°C global warming at the end of the century³⁰. Histograms show the distributions of invasive species richness. Reproduced from Kelly *et al.* (2014).

³⁰ 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
England	High (High confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)	High (Medium confidence)
Northern Ireland	Medium (High confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)
Scotland	Medium (high confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)	Medium (Medium confidence)
Wales	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)

Table 3.41 Adaptation scores for risks to freshwater species and habitats from pests, pathogens and invasive species			
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)

3.13.3 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
Urgency score	More action needed	More action needed	More action needed	More action needed
Confidence	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 2080s³¹, 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.

³¹ 50th 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.

Table 3.43 Magnitude scores for opportunities to freshwater species and habitats from new species colonisations					
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 confidence)	Low (low confidence)	Low (low confidence)	Low (Low confidence)	Low (Low confidence)
Northern Ireland	Low (Low confidence)	Low (low confidence)	Low (low confidence)	Low (Low confidence)	Low (Low confidence)
Scotland	Low (Low confidence)	Low (low confidence)	Low (low confidence)	Low (Low confidence)	Low (Low confidence)
Wales	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 2080s³², although the species at a site and assemblages could change.

³² 50th 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)

Table 3.44 Adaptation scores for opportunities to freshwater species and habitats from new species colonisations			
Are the opportunities going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)	Partially (Low confidence)

3.14.3 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)

Table 3.45 Urgency scores for opportunities to freshwater species and habitats from new species colonisations				
Country	England	Northern Ireland	Scotland	Wales
Urgency Score	Sustain current action	Sustain current action	Sustain current action	Sustain current action
Confidence	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 CO₂ 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 feedbacks³³, 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

³³ RCP8.5 concentrations pathway, which would either require CO₂ 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 CCRA have extensively evaluated the role of acidification caused by the oceanic uptake of CO₂. 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 CCRA, 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 (Régnier *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 CO₂ concentrations reaching 940 ppm in 2100³⁴ () 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 CO₂ 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

³⁴ RCP8.5 concentrations pathway, which would either require CO₂ 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 CO₂, 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
England	Medium (Medium confidence)	High (low confidence)	High (Low confidence)	High (low confidence)	High (low confidence)
Northern Ireland	Medium (Medium confidence)	High (low confidence)	High (Low confidence)	High (low confidence)	High (low Confidence)
Scotland	Medium (Medium confidence)	High (low confidence)	High (Low confidence)	High (low confidence)	High (low confidence)
Wales	Medium (Medium confidence)	High (low confidence)	High (Low confidence)	High (low confidence)	High (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 2566km²) in recent years and the next stage will involve identification of necessary management measures to bring the network into 'favourable condition' (currently only 115km² 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.

Table 3.48 Urgency scores for risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures

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

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) (Faillettaz 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)

Table 3.49 Magnitude scores for opportunities to marine species, habitats and fisheries from changing climatic conditions					
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 (low confidence*)	Med-High (low confidence)	High (Low confidence)	High (Low confidence)	High (low confidence)
Northern Ireland	Medium (low confidence*)	Med-High (low confidence)	High (Low confidence)	High (Low confidence)	High (low confidence)
Scotland	Medium (low confidence*)	Med-High (low confidence)	High (Low confidence)	High (Low confidence)	High (low confidence)
Wales	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. Airoldi 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)

Table 3.51 Urgency scores for opportunities to marine species, habitats and fisheries from changing climatic conditions				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	Further investigation	Further investigation	Further investigation	Further investigation
Confidence	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 winkle (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)

Table 3.52 Magnitude scores for risks to marine 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
England	Medium (medium confidence*)	High (low confidence)	High (low confidence)	High (low confidence)	High (Low confidence)
Northern Ireland	Medium (medium confidence*)	High (low confidence)	High (low confidence)	High (low confidence)	High (Low confidence)
Scotland	Medium (medium confidence*)	High (low confidence)	High (low confidence)	High (low confidence)	High (Low confidence)
Wales	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)

Table 3.53 Adaptation scores for risks to marine species and habitats from pests, pathogens and invasive species			
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)

3.17.3 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)

Table 3.54 Urgency scores for risks to marine species and habitats from pests, pathogens and invasive species				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	More action needed	More action needed	More action needed
Confidence	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 CCRA, 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 19th 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 CCRA, 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 ≥ 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
England	Medium (Medium confidence)	High (low-medium confidence)	High (low-medium confidence)	High (low-medium confidence)	High (low-medium confidence)
Northern Ireland	Medium (Low confidence)	High (low confidence)	High (low confidence)	High (Low confidence)	High (Low confidence)
Scotland	Medium (Medium confidence)	High (low-medium confidence)	High (low-medium confidence)	High (low-medium confidence)	High (low-medium confidence)
Wales	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 (2nd 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: Slingso, 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-Roswell, 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	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	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	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	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 level 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 contribute 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.

Table 3.61 Urgency Score for Risks and opportunities to coastal species and habitats due to coastal flooding, erosion, and climate factors				
Country	England	Northern Ireland	Scotland	Wales
Urgency score	More action needed	More action needed	More action needed	More action needed
Confidence	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.

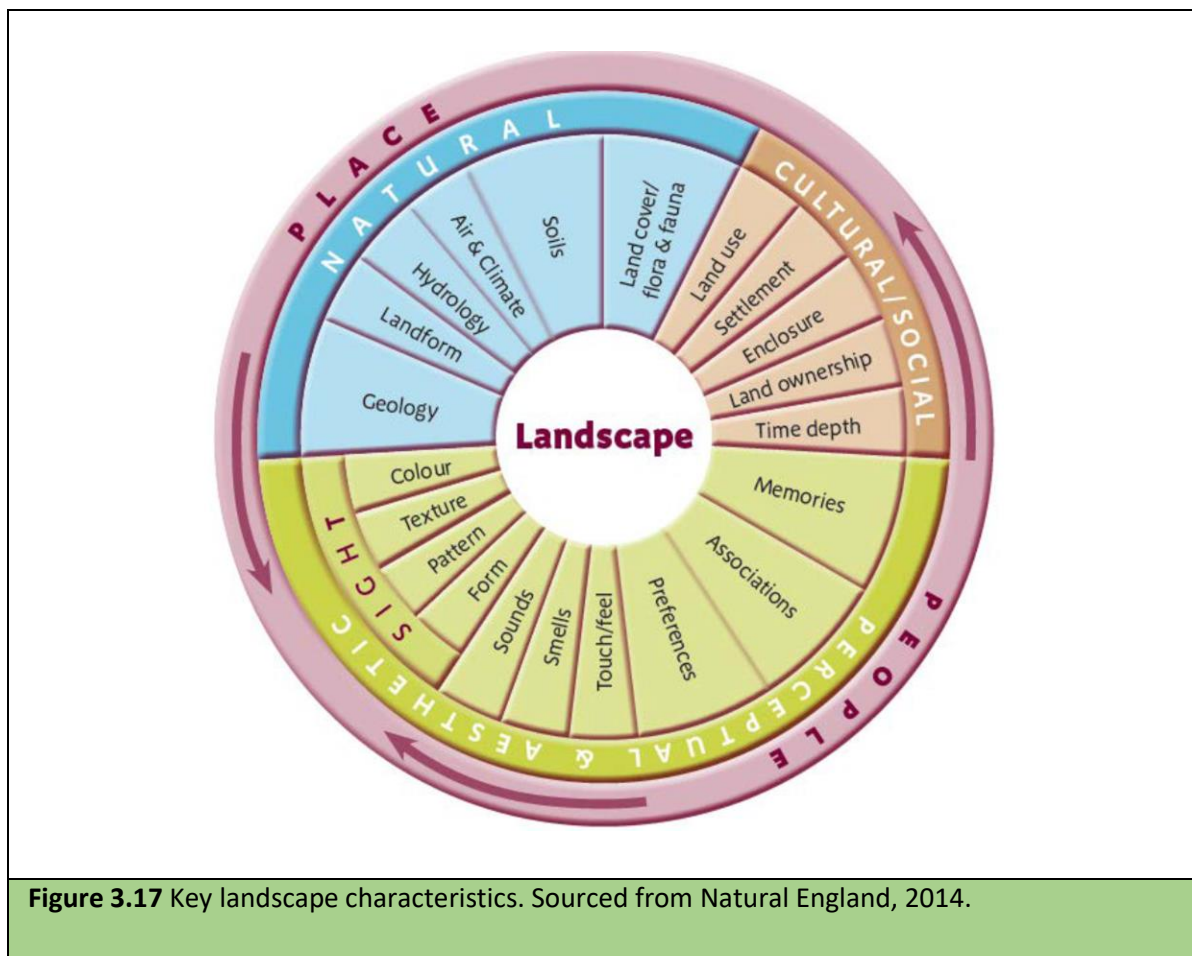


Figure 3.17 Key landscape characteristics. Sourced from Natural England, 2014.

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
England	Medium (Low confidence)	Med-High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Northern Ireland	Medium (Low confidence)	Med-High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Scotland	Medium (Low confidence)	Med-High (Low confidence)	High (Low confidence)	High (Low confidence)	High (Low confidence)
Wales	Medium (Medium confidence)	Med-High (Low confidence)	High (Low confidence)	High (Low confidence)	High (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)

Table 3.63 Adaptation Scores for risks and opportunities from climate change to landscape character			
Are the risks going to be managed in the future?			
England	Northern Ireland	Scotland	Wales
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)

Table 3.64 Urgency Score for risks and opportunities from climate change to landscape character				
	England	Northern Ireland	Scotland	Wales
Urgency score	Further investigation	Further investigation	Further investigation	Further investigation
Confidence	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.

Table 3.65 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.				
Mitigation option	Context dependency	Climate risks to effectiveness of mitigation measure	Synergies with adaptation	Trade-offs with adaptation
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 ₄ and N ₂ O reductions)	Land capability grade / class	Temperature; precipitation; humidity; soil moisture; CO ₂	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 ₂ -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.

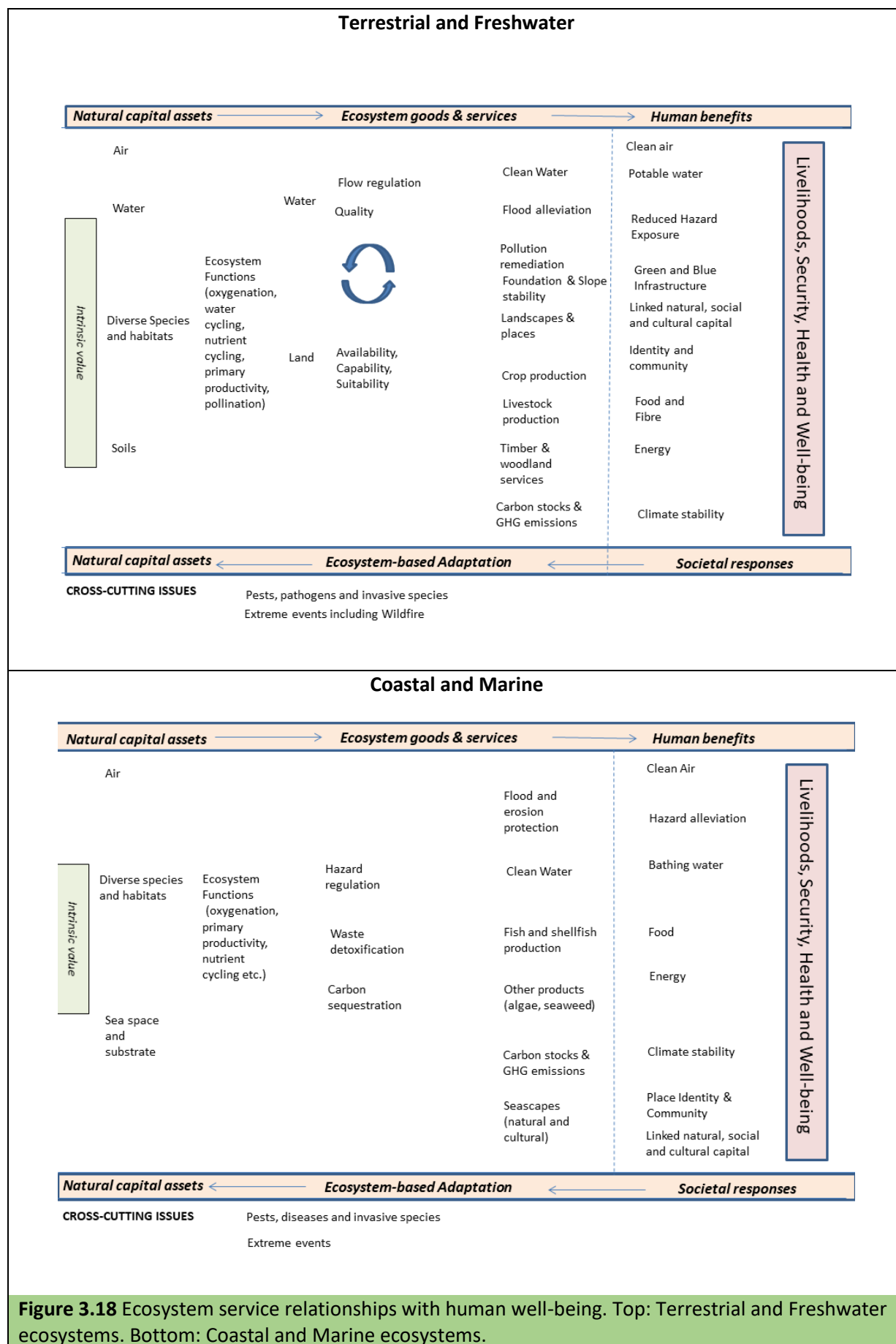


Figure 3.18 Ecosystem service relationships with human well-being. Top: Terrestrial and Freshwater ecosystems. Bottom: Coastal and Marine ecosystems.

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.

3.21. References

- Aarnes, O.J., Reistad, M., Breivik, Ø., Bitner-Gregersen, E., Ingolf Eide, L., Gramstad, O. *et al.* (2017). Projected changes in significant wave height toward the end of the 21st century: Northeast Atlantic. *Journal of Geophysical Research: Oceans*, 122, 3394–3403. <http://doi.org/10.1002/2016JC012521>
- AbdElgawad, H., Peshev, D., Zinta, G., Van Den Ende, W., Janssens, I.A., Asard, H. (2014). Climate extreme effects on the chemical composition of temperate grassland species under ambient and elevated CO₂: A comparison of fructan and non-fructan accumulators. *PLoS ONE*, 9, 1–13. <https://doi.org/10.1371/journal.pone.0092044>
- ABPMer (2019). OMREG <https://www.omreg.net/>
- AECOM (2018). Adaptation actions in the natural environment – what works? Retrieved from <https://www.theccc.org.uk/wp-content/uploads/2018/11/Adaptation-actions-in-the-Natural-Environment-what-works-final.pdf>
- ADAS. (2019). Research to update the evidence base for indicators of climate-related risks and actions in England Retrieved from <https://www.theccc.org.uk/publication/research-to-update-the-evidence-base-for-indicators-of-climate-related-risks-and-actions-in-england-adas/>
- Adger, W.N. Barnett, J., Chapin III, F.S., and Ellemor, H. (2011). This must be the place: underrepresentation of identity and meaning in climate change decision-making. *Global Environmental Politics*, 11(2), 1 - 25. https://doi.org/10.1162/GLEP_a_00051
- ADIS. https://ec.europa.eu/food/animals/animal-diseases/not-system_en
- Airoldi, L. Balata, D., Beck, M.W. (2008). The Gray Zone: Relationships between habitat loss and marine diversity and their applications in conservation. *Journal of Experimental Marine Biology and Ecology*, 366, 8-15. <https://doi.org/10.1016/j.jembe.2008.07.034>
- Alaoui, A., Rogger, M., Peth, S., Blöschl, G. (2018). Does soil compaction increase floods? A review. *Journal of Hydrology*, 557, 631 - 642. <https://doi.org/10.1016/j.jhydrol.2017.12.052>
- Alexander, K.A., Hobday, A., Cvitanovic, C., Ogier, E., Nash, K., Cottrell, R.S. *et al.* (2018). Progress in integrating natural and social science in marine ecosystem-based management research. *Marine and Freshwater Research* 70(1), 71-83. <https://doi.org/10.1071/MF17248>
- Alexander, K.N.A. (2019). Saproxyllic Invertebrate Survey of Wye Valley Woodlands Special Area of Conservation (SAC) in 2018 (NRW Evidence Report No: 320). Retrieved from <https://cdn.cyfoethnaturiol.cymru/media/688202/eng-report-320-saproxyllic-invertebrate-survey-of-wye-valley-woodlands-sac-copy.pdf>
- Alexander, P., Moran, D., Rounsevell, M.D., and Smith, P. (2013). Modelling the perennial energy crop market: the role of spatial diffusion. *Journal of the Royal Society Interface*, 10(88), 20130656. <https://doi.org/10.1098/rsif.2013.0656>
- Alison, J., Emmett, B.A., Robinson, D.A., Smart, S.M., Thomas, A. (2019). Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP) – ERAMMP Year 1 Report 21: GMEP Outstanding Analysis Part 2 – Revisiting Trends in Topsoil Carbon from CS2007 to GMEP 2013-2016. Retrieved from https://erammp.wales/sites/default/files/ERAMMP_Rpt_21_Soil_Carbon_v1.0.pdf
- Álvarez-Fernández, I., Freire, J., Naya, I., Fernández, N., Sánchez-Carnero, N. (2020). Failures in the design and implementation of management plans of Marine Protected Areas: An empirical analysis for the North-east Atlantic Ocean. *Ocean & Coastal Management*, 192, 105178. <https://doi.org/10.1016/j.ocecoaman.2020.105178>
- Amundson, J.L., Mader, T.L., Rasby, R.J., Hu, Q.S. (2006). Environmental effects on pregnancy rate in beef cattle. *Journal of Animal Science*, 84(12), 3415–3420. <https://doi.org/10.2527/jas.2005-611>

- Anderegg, W.R.L., Trugman, A.T., Badgley, G., Konings, A.G., Shaw, J. (2020). Divergent forest sensitivity to repeated extreme droughts. *Nature Climate Change*. <https://doi.org/10.1038/s41558-020-00919-1>
- Angus, S. (2018). Beyond the meta-ecosystem? The need for a multi-faceted approach to climate change planning on coastal wetlands: An example from South Uist, Scotland. *Ocean & Coastal Management*, 165, 334–345. <https://doi.org/10.1016/j.ocecoaman.2018.08.013>
- Angus, S., and Hansom, J.D. (2021). Enhancing the resilience of high-vulnerability, low-elevation coastal zones. *Ocean & Coastal Management*, 200, 105414. <https://doi.org/10.1016/j.ocecoaman.2020.105414>
- Anthony, S. (2019). *Mapping Soil Water Storage Capacity and Soil Compaction Effect for Wales*. Welsh Government Soil Policy Evidence Programme Report (SPEP 2018-19/10). Retrieved from <https://gov.wales/sites/default/files/publications/2020-11/water-storage-capacity-soils-scoping-report.pdf>
- Armstrong, A., Page, T., Thackeray, S.J., Hernandez, R.R., and Jones, I.D. (2020). Integrating environmental understanding into freshwater floatovoltaic deployment using an effects hierarchy and decision trees. *Environmental Research Letters*, 15, 114055. <https://doi.org/10.1088/1748-9326/abbf7b>
- Armstrong, E. (2016). The Farming Sector in Wales. Research Briefing: National Assembly of Wales Commission (16 - 053). Retrieved from <https://senedd.wales/research%20documents/16-053-farming-sector-in-wales/16-053-web-english2.pdf>
- Armstrong, H., Gill, R., Mayle, B., Trout, R. (2020). Protecting trees from deer: an overview of current knowledge and future work. Retrieved from https://www.forestresearch.gov.uk/documents/321/FR0102deer_TeTD1Jj.pdf
- Arnell, N.W., Freeman, A. (2021). The effect of climate change on agro-climatic indicators in the UK. *Climatic Change* 165, 40. <https://doi.org/10.1007/s10584-021-03054-8>
- Arnell, N., Freeman, N., Gazzard, R. (2021). The effect of climate change on indicators of fire danger in the UK. *Environmental Research Letters*. <https://doi.org/10.1088/1748-9326/abd9f2>
- Arnscheidt, J., Jordan, P., Li, S., McCormick, S., McFaul, R., McGrogan, H.J. *et al.* (2007). Defining the sources of low-flow phosphorus transfers in complex catchments. *Sci. Total Environ*, 382(1), 1–13. <https://doi.org/10.1016/j.scitotenv.2007.03.036>
- Asseng, S., Martre, P., Maiorano, A., Rötter, R.P., O’Leary, G.J., Glenn, J. *et al.* (2018). Climate change impact and adaptation for wheat protein. *Global Change Biology*, 25(1). <https://doi.org/10.1111/gcb.14481>
- Assis, J.V., Lucas, A., Bárbara, I., Álvares Serrãoa, E. (2016). Future climate change is predicted to shift long-term persistence zones in the cold-temperate kelp *Laminaria hyperborea*. *Marine Environmental Research*, 113, 174-182. <https://doi.org/10.1016/j.marenvres.2015.11.005>
- Atkins. (2019). *A framework for the production of Drainage and Wastewater Management Plans Report prepared for WaterUK*. Retrieved from https://www.water.org.uk/wp-content/uploads/2020/01/Water_UK_DWMP_Framework_Report_Main_September-2019.pdf
- Atkins Global. (2019). Scoping study: ecosystem services and natural capital costs of Invasive Non-Native Species (INNS) in the UK. Report to Defra. Retrieved from <http://scienceresearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=20315>
- Ausden, M., Bradbury, R.B., Brown, A., Eaton, M., Lock, L., Pearce-Higgins, J. (2015). Climate change and Britain’s birdlife: What might we expect? *British Wildlife*, 26.3, 161-174. Retrieved from <https://www.britishwildlife.com/article/volume-26-number-3-page-161-174>
- Ballinger, R.C., and Dodds, W. (2020). Shoreline management plans in England and Wales: a scientific and transparent process. *Marine Policy*, 111(102689). <https://doi.org/10.1016/j.marpol.2017.03.009>

- Barbet-Massin, M., Rome, Q., Villemant, C., Courchamp, F. (2018). Can species distribution models really predict the expansion of invasive species? *PLoS ONE*, 13, e0193085. <https://doi.org/10.1371/journal.pone.0193085>
- Barracough, D., Smith, P., Worrall, F., Black, H.I.J., Bhogal, A. (2015) Is there an impact of climate change on soil carbon contents in England and Wales? *European Journal of Soil Science*, 66, 451-462. <https://doi.org/10.1111/ejss.12253>
- Barrow, C., Newell Price, J.P., Brown, C.F., Dyer, R., Clarke, S., Joynt, R. et al. (2020). A review to consider the practical implications of the UK Climate Change Predictions 2018 (UKCP18). Report to the Welsh Government (CSCP12). Available from the Welsh Government on request
- Bassu, S., Asseng, S., Richards, R. (2011). Yield benefits of triticale traits for wheat under current and future climates. *Field Crops Research*, 124, 14–24. <https://doi.org/10.1016/j.fcr.2011.05.020>
- Bastin, J.F., Finegold, Y.G., C., Gellie, N., Lowe, A., Mollicone, D., Rezende, M. et al. (2019). Response to comments on “The global tree restoration potential” *Science*, 366(6463), eaay8108. <https://doi.org/10.1126/science.aay8108>
- Baudron, A.R., Needle, C.L., Rijnsdorp, A.D., Tara Marshall, C. (2014). Warming temperatures and smaller body sizes: synchronous changes in growth of North Sea fishes. *Global Change Biology*, 20(4), 1023–1031. <https://doi.org/10.1111/gcb.12514>
- Baylis, M. (2017). Potential impact of climate change on emerging vector-borne and other infections in the UK. *Environ Health*, 16, 112. <https://doi.org/10.1186/s12940-017-0326-1>
- BBC. (2020). <https://www.bbc.co.uk/news/uk-england-cumbria-53693300>
- BBSRC. (2016). New vision and high-level research strategy for UK Animal and Plant Health Research. Retrieved from <https://bbsrc.ukri.org/documents/1601-animal-and-plant-health-report-3/>
- Beaumont, N., Hattam, C., Mangi, S., Moran, D., van Soest, D., Jones, L., Tobermann, M. (2010). National Ecosystem Assessment (NEA): Economic Analysis. Coastal Margin and Marine Habitats, Final Report. Retrieved from <http://uknea.unep-wcmc.org/LinkClick.aspx?fileticket=O%2B8tTp%2F5ZPg%3D&tabid=82>
- Beaumont, N.J., Jones, L., Garbutt, A., Hansom, J.D., Toberman, M. (2014). The value of carbon sequestration and storage in coastal habitats. *Estuarine, Coastal and Shelf Science*, 137, 32–40. <https://doi.org/10.1016/j.ecss.2013.11.022>
- Bebber, D., Ramotowski, M., Gurr, S. (2013). Crop pests and pathogens move polewards in a warming world. *Nature Clim Change* 3, 985–988. <https://doi.org/10.1038/nclimate1990>
- BeeBase. (2021). Asian Hornet. Retrieved from <https://nationalbeeunit.com/index.cfm?sectionid=117>
- Belcher, C., Brown, I., Clay, G., Doerr, S., Elliott, A., Gazzard, R., Kettridge, N., Morison, J., Perry, M., Santin, C., Smith, T. (2021). UK Wildfires and their Climate Challenges. Report prepared for the CCRA3 Technical Report. <https://www.ukclimaterisk.org/independent-assessment-ccra3/research-supporting-analysis/>
- Bell, G., Naumann, E-K., Medcalf, K. (2019). Application of ALC and UKCP18 Data for Modelling Crop Suitability. Report to the Welsh Government. Available on request from The Welsh Government
- Bell, G., Naumann, E-K., Medcalf, K. (2020). Tree Suitability Modelling – Planting Opportunities for Sessile Oak and Sitka Spruce in Wales in a Changing Climate. *Report to the CCC*. Environment Systems Ltd, Ceredigion, Wales: <https://www.theccc.org.uk/wp-content/uploads/2020/01/Environment-Systems-Ltd-2020-Tree-Suitability-Modelling---Planting-Opportunities-for-Sessile-Oak-and-Sitka-Spruce-in-Wales-in-a-Changing-Climate.pdf>

- Bell, J., Inman, G., and McDowell, M. (2018). Straw and Forage Study: A Review commissioned for the Scottish Government. Retrieved from <https://www.gov.scot/publications/straw-and-forage-study-sruc-research-report/>
- Bell, V.A., Kay, A.L., Davies, H.N., Jones, R.G. (2016). An assessment of the possible impacts of climate change on snow and peak river flows across Britain. *Climatic Change*, 136, 539–553. <https://doi.org/10.1007/s10584-016-1637-x>
- Bellarby, J., Wattenbach, M., Tuck, G., Glendining, M.J., Smith, P. (2010). The potential distribution of bioenergy crops in the UK under present and future climate. *Biomass Bioenergy*, 34, 1935–1945. <https://doi.org/10.1016/j.biombioe.2010.08.009>
- Bellard, C., Jeschke, J.M., Leroy, B., Mace, G.M. (2018). Insights from modeling studies on how climate change affects invasive alien species geography. *Ecology and Evolution*, 8(11), 5688-5700. <https://doi.org/10.1002/ece3.4098>
- Beltrán, A., Maddison, D., and Elliott, R.J. (2018). Assessing the Economic Benefits of Flood Defenses: A Repeat-Sales Approach. *Risk analysis: an official publication of the Society for Risk Analysis*, 38(11), 2340-2367. <https://doi.org/10.1111/risa.13136>
- Ben-Ari, T., Boé, J., Ciais, P., Lecerf, R., Van der Velde, M., Makowski, D. (2018). Causes and implications of the unforeseen 2016 extreme yield loss in the breadbasket of France. *Nature Communications*, 9(1), 1-10. <https://doi.org/10.1038/s41467-018-04087-x>
- Benaud, P., Anderson, K., Evans, M., Farrow, L., Glendell, M., James, M.R. et al. (2020). National-scale geodata describe widespread accelerated soil erosion. *Geoderma* 371, 114378. <https://doi.org/10.1016/j.geoderma.2020.114378>
- Benyon, R., Barham, P., Edwards, J., Kaiser, M., Owens, S., de Rozarieux, N., Roberts, C., Sykes, B. (Review panel members). (2020). *Benyon Review Into Highly Protected Marine Areas*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/890484/hpma-review-final-report.pdf
- Berdeni, D., Williams, J., Dowers, J. (2020). Assessment of the impact of tree planting on Welsh organo-mineral soils. Welsh Government Soil Policy Evidence Programme Report (SPEP2019-20/02). Available from the the Welsh Government on request
- Berry, P.M., Brown, S., Chen, M., Kontogianni, A., Rowlands, O., Simpson, G., Skourtos, M. (2014). Cross-sectoral interactions of adaptation and mitigation measures. *Climate Change*, 128, 381-393. <https://doi.org/10.1007/s10584-014-1214-0>
- Berry, P., Broadmeadow, M., Morecroft, M. (2019). About Drought Woodlands report card. Retrieved from: <https://aboutdrought.info/wp-content/uploads/2020/07/AboutDrought-ReportCard-Woodlands-Final.pdf>
- Berry, R., Dwyer, J., Gaskell, P., Lake, J., Powell, J., Young, I. (2019). LANDMAP, Landscape and a Changing Climate. <https://cdn.naturalresources.wales/media/689497/eng-evidence-report-314-landscape-and-changing-climate.pdf>
- Berryman, A.A. (1982). Biological Control, Thresholds, and Pest Outbreaks. *Environmental Entomology*, 11(3), 544–549. <https://doi.org/10.1093/ee/11.3.544>
- Betts, R.A., Alfieri, L., Bradshaw, C., Caesar, J., Feyen, L., et al. (2018). Changes in climate extremes, fresh water availability and vulnerability to food insecurity projected at 1.5°C and 2°C global warming with a higher-resolution global climate model. *Philos. Trans. R. Soc. A Sci.* 376: 20160452 <https://doi.org/10.1098/rsta.2016.0452>
- Biological Records Centre. (2021). *Spartina anglica*. Retrieved from <https://www.brc.ac.uk/plantatlas/plant/spartina-anglica>

- Birk, S., Chapman, D., Carvalho, L., Spears, B.M., Andersen, H.E., Argillier, C. *et al.* (2020). Impacts of multiple stressors on freshwater biota across scales and ecosystems. *Nature Ecology & Evolution*, 4, 1060–1068. <https://www.nature.com/articles/s41559-020-1216-4>
- Black, K., and Hughes, A. (2017). *Future of the Sea: Trends in Aquaculture. Foresight Future of the Sea Review.*
[https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/635209/Future of the sea - trends in aquaculture FINAL NEW.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/635209/Future_of_the_sea_-_trends_in_aquaculture_FINAL_NEW.pdf)
- Blunden, J., and Arndt, D.S. (Eds). (2020). State of the Climate in 2019. *Bull. Amer. Meteor. Soc*, 101(8), Si–S429 <https://doi.org/10.1175/2020BAMSStateoftheClimate.1>
- Boardman, J., Bateman, S., Seymour, S. (2017). Understanding the influence of farmer motivations on changes to soil erosion risk on sites of former serious erosion in the South Downs National Park, UK. *Land Use Policy*, 60, 298-312. <https://doi.org/10.1016/j.landusepol.2016.10.043>
- Boerema, A., Geerts, L., Oosterlee, L., Temmerman, S., and Meire P. (2016). Ecosystem service delivery in restoration projects: the effect of ecological succession on the benefits of tidal marsh restoration. *Ecology and Society*, 21(2), 10. <http://doi.org/10.5751/ES-08372-210210>
- Boerlage, A.S., Ashby, A., Herrero, A., Reeves, A., Gunn, G.J., and Rodger, H.D. (2020). Epidemiology of marine gill diseases in Atlantic salmon (*Salmo salar*) aquaculture: a review. *Reviews in Aquaculture*, 12(4), 2140-2159. <https://doi.org/10.1111/raq.12426>
- Boggs, C.L. (2016). The fingerprints of global climate change on insect populations. *Current Opinion in Insect Science*, 17, 69-73. <https://doi.org/10.1016/j.cois.2016.07.004>
- Bond-Lamberty, B., Bailey, V.L., Chen, M., Gough, C.M., and Vargas, R. (2018). Globally rising soil heterotrophic respiration over recent decades. *Nature*, 560, 80–83. <https://doi.org/10.1038/s41586-018-0358-x>
- Boon, P.J., Clarke, S.A., and Copp, G.H. (2020). Alien species and the EU Water Framework Directive: a comparative assessment of European approaches. *Biological Invasions*, 22, 1497–1512 <https://doi.org/10.1007/s10530-020-02201-z>
- Borja, A., Elliott, M., Andersen, J.H., Berg, T., Carstensen, J., Halpern, B.S. *et al.* (2016). Overview of integrative assessment of marine systems: the ecosystem approach in practice. *Frontiers in Marine Science* 3(2). <https://doi.org/10.3389/fmars.2016.00020>
- Boulton, C. A., Ritchie, P.D.L., and Lenton, T.M. (2020). Abrupt changes in Great Britain vegetation carbon projected under climate change. *Global Change Biology*, 26(8), 4436-4448. <https://doi.org/10.1111/gcb.15144>
- Bowes, M.J., Loewenthal, M., Read, D.S., Hutchins, M.G., Prudhomme, C., Armstrong, L.K. *et al.* (2016). Identifying multiple stressor controls on phytoplankton dynamics in the River Thames (UK) using high-frequency water quality data. *Science of the Total Environment*, 569-570, 1489-1499. <https://doi.org/10.1016/j.scitotenv.2016.06.239>
- Boyd, I., Freer-Smith, P., Gilligan, C., and Godfray, C. (2013). The consequences of tree pests and diseases for ecosystem services. *Science*, 342, 823–840. <https://doi.org/10.1126/science.1235773>
- Bradbury, R.B., Pearce-Higgins, J.W., Wotton, S.R., Conway, G.J., and Grice, P.V. (2011). The influence of climate and topography in patterns of territory establishment in a range-expanding bird. *Ibis*, 153, 336-344. <https://doi.org/10.1111/j.1474-919X.2011.01106.x>
- Bradford, M.A., Wieder, W.R., Bonan, G.B., Fierer, N., Raymond, P.A., Crowther, T.W. (2016). Managing uncertainty in soil carbon feedbacks to climate change. *Nature Climate Change*, 6, 751 - 758. <https://doi.org/10.1038/nclimate3071>

- Bradshaw, C.D., Hemming, D., Baker, R., Everatt, M., Eyre, D., Korycinska, A. (2019). A novel approach for exploring climatic factors limiting current pest distributions: A case study of *Bemisia tabaci* in north-west Europe and assessment of potential future establishment in the United Kingdom under climate change. *PLoS ONE*, 14. <https://doi.org/10.1371/journal.pone.0221057>
- Branson, J., Hornby, D.D., Campbell Sutton, A., Gubbins, G. (2018). *Mapping pests and diseases in historic parks and gardens*.
<https://research.historicengland.org.uk/PrintReport.aspx?i=16030&ru=%2FResults.aspx%3Fp%3D1%26n%3D10%26rn%3D30%26ry%3D2018%26ns%3D1>
- Bresnan, E., Baker-Austin, C., Campos, C.J.A., Davidson, K., Edwards, M., Hall, A., McKinney, A., and Turner, A.D. (2020). Impacts of climate change on human health, HABs and bathing waters, relevant to the coastal and marine environment around the UK. *MCCIP Science Review*, 521–545.
<https://doi.org/10.14465/2020.arc22.hhe>
- Bright, G. (2019). Measuring natural capital: towards accounts for the UK and a basis for improved decision-making. *Oxford Review of Economic Policy*, 35, 88-108 <https://doi.org/10.1093/oxrep/gry022>
- Briggs, M.A., Johnson, Z.C., Snyder, C.D., Hitt, N.P., Kurylyk, B. L., Lautz, L. *et al.* (2018). Inferring watershed hydraulics and cold-water habitat persistence using multi-year air and stream temperature signals. *Science of the Total Environment*, 636, 1117-1127. <https://doi.org/10.1016/j.scitotenv.2018.04.344>
- British Pest Control Association (2020). Becoming COVID-19 secure. Retrieved from
https://bpca.org.uk/write/MediaUploads/News%20and%20Blog/2020-05-18-%20Becoming%20Covid19%20secure%20guide%20for%20pest%20professionals/BPCA_-_Covid-19_guidance_FINAL.pdf
- Britton, J. R., Cucherousset, J., Davies, G.D., Godard, M.J., Copp, G.H. (2010). Non-native fishes and climate change: Predicting species responses to warming temperatures in a temperate region. *Freshwater Biology*, 55(5), 1130– 1141. <https://doi.org/10.1111/j.1365-2427.2010.02396.x>
- Brooker, R.W., Brewer, M.J., Britton, A.J., Eastwood, A., Ellis, C., Gimona, A. *et al.* (2018). Tiny niches and translocations: The challenge of identifying suitable recipient sites for small and immobile species. *Journal of Applied Ecology*, 55, 621– 630. <https://doi.org/10.1111/1365-2664.13008>
- Broome, A., Mitchell, R.J. (2017). Ecological impacts of ash dieback and mitigation methods. Forest Commission Research Note 029. *Forest Research*.
<https://www.forestresearch.gov.uk/research/ecological-impacts-of-ash-dieback-and-mitigation-methods/>
- Brown, A., and Webber, J. (2008). *Red band needle blight of conifers in Great Britain*. Research Note FCRN002. Retrieved from Edinburgh:
<https://www.forestresearch.gov.uk/documents/2341/fcrn002.pdf>
- Brown, I. (2017). Climate change and soil wetness limitations for agriculture: spatial risk assessment framework with application to Scotland. *Geoderma* 285, 173-184.
<https://doi.org/10.1016/j.geoderma.2016.09.023>
- Brown, I. (2020). Challenges in delivering climate change policy through land use targets for afforestation and peatland restoration. *Environmental Science & Policy*, 107, 36-45.
<https://doi.org/10.1016/j.envsci.2020.02.013>
- Brown, I., and Castellazzi, M. (2015). Changes in climate variability with reference to land quality and agriculture in Scotland. *International Journal of Biometeorology*, 59(6), 717-732.
<https://doi.org/10.1007/s00484-014-0882-9>
- Brown, J.K.M., Beeby, R. and Penfield, S. (2019). Yield instability of winter oilseed rape modulated by early winter temperature. *Sci. Rep.* 9, 6953. <https://doi.org/10.1038/s41598-019-43461-7>

- Brown, K., and Mijic, A. (2019). Integrating green and blue spaces into our cities: Making it happen. Briefing paper. Retrieved from Imperial college, London.
<https://www.imperial.ac.uk/grantham/publications/briefing-papers/integrating-green-and-blue-spaces-into-our-cities-making-it-happen-.php>
- Brown, K., Naylor, L.A., Quinn, T. (2017). Making Space for Proactive Adaptation of Rapidly Changing Coasts: A Windows of Opportunity Approach. *Sustainability*, 9, 1408. <https://doi.org/10.3390/su9081408>
- Brown, S., Nicholls, R.J., Vafeidis, A., Hinkel, J., and Watkiss, P. (2011). The Impacts and Economic Costs of Sea-Level Rise in Europe and the Costs and Benefits of Adaptation. Summary of Results from the EC RTD ClimateCost Project. In Watkiss, P (Editor), 2011. The ClimateCost Project. Final Report. Volume 1: Europe. Published by the Stockholm Environment Institute, Sweden. ISBN 978-91-86125-35-6.
http://www.climatecost.cc/images/Policy_brief_2_Coastal_10_lowres.pdf
- Burden, A., Smeaton, C., Angus, S., Garbutt, A., Jones, L., Lewis, H.D., Rees, S.M. (2020). Impacts of climate change on coastal habitats relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 228–255. <https://doi.org/10.14465/2020.arc11.chb>
- Burge, C.A., Eakin, C.M., Friedman, C.S., Froelich, B., Hershberger, P.K., Hofmann, E.E. *et al.* (2014). Climate Change Influences on Marine Infectious Diseases: Implications for Management and Society. *Annual Review of Marine Science*, 6, 249-277. <https://doi.org/10.1146/annurev-marine-010213-135029>
- Burgess, K., Jay, H., Nicholls, R.J., Green, C. and Penning-Rowsell, E.C. (2007) Assessment of future coastal erosion risk. In: Future flooding and coastal erosion risks [Eds. Thorne, C., Green, C. and Penning-Rowsell, E.C.], Thomas Telford, London: 280-293.
<https://www.icevirtuallibrary.com/doi/book/10.1680/ffacer.34495>
- Burgin, L., Ekström, M., Dessai, S. (2017). Combining dispersion modelling with synoptic patterns to understand the wind-borne transport into the UK of the bluetongue disease vector. *Int J Biometeorol* 61, 1233–1245. <https://doi.org/10.1007/s00484-016-1301-1>
- Burns, F., Eaton, M., Barlow, A., Beckmann, K.E., Björn, C., Brereton, T. *et al.* (2016). Agricultural management and climatic change are the major drivers of biodiversity change in the UK. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0151595>
- Burt, T., Boardman, J., Foster, I., Howden, N. (2016). More rain, less soil: long-term changes in rainfall intensity with climate change. *Earth’ Surface Processes and Landforms*, 41(4).
<https://doi.org/10.1002/esp.3868>
- Bussi, G., Janes, V., Whitehead, P.G., Dadson, S.J., Holman, I.P. (2017). Dynamic response of land use and river nutrient concentration to long-term climatic changes. *Science of the Total Environment*, 590-591, 818-831. <https://doi.org/10.1016/j.scitotenv.2017.03.069>
- Bussi, G., Whitehead, P.G., Bowes, M.J., Read, D.S., Prudhomme, C., Dadson, S.J. (2016). Impacts of climate change, land-use change and phosphorus reduction on phytoplankton in the River Thames (UK). *Science of the Total Environment*, 572, 1507-1519. <https://doi.org/10.1016/j.scitotenv.2016.02.109>
- Callaway, R., Shinn, A.P., Grenfell, S., Bron, J.E., Burnell, G., Cottier-Cook, E.J. *et al.* (2012). Review of Climate Change Impacts on Marine Aquaculture in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 22(3), 389–421. <https://doi.org/10.1002/aqc.2247>
- Cambridge Econometrics. (2019). A consistent set of socioeconomic dimensions for the CCRA3 Evidence Report research projects. Retrieved from https://www.ukclimaterisk.org/wp-content/uploads/2020/07/Socioeconomic-Dimensions-Final-Report_CE.pdf

- Cammarano, D., Hawes, C., Squire, G., Holland, J., Rivington, M., Murgia, T. *et al.* (2019). Rainfall and temperature impacts on barley (*Hordeum vulgare* L.) yield and malting quality in Scotland. *Field Crops Research*, 241(107559). <https://doi.org/10.1016/j.fcr.2019.107559>
- Capaldi, C.A., Passmore, H.A., Nisbet, E.K., Zelenski, J.M. and Dopko, R.L. (2015). Flourishing in Nature: A Review of the Benefits of Connecting with Nature and its Application as a Wellbeing Intervention. *International Journal of Wellbeing*, 5(4), 1-16. <https://doi.org/10.5502/ijw.v5i4.449>
- Capinha, C., Larson, E.R., Tricarico, E., Olden, J.D., Gherardi, F. (2013). Effects of Climate Change, Invasive Species, and Disease on the Distribution of Native European Crayfishes. *Conservation Biology*, 27(4), 731-740. <https://doi.org/10.1111/cobi.12043>
- Capuzzo, E., Lynam, C.P., Barry, J., Stephens, D., Forster, R.M., Greenwood, N. *et al.* (2018). A decline in primary production in the North Sea over 25 years, associated with reductions in zooplankton abundance and fish stock recruitment. *Global Change Biology*, 24(1), e352–e364. <https://doi.org/10.1111/gcb.13916>
- Caravaggi, A. Leach, K., Santilli, F., Rintala, J., Helle, P., Tiainen, J. *et al.* (2017). Niche overlap of mountain hare subspecies and the vulnerability of their ranges to invasion by the European hare; the (bad) luck of the Irish. *Biological Invasions*, 19, 655 - 674. <https://doi.org/10.1007/s10530-016-1330-z>
- Carlson, A.K., Taylor, W.W., Schlee, K.M., Zorn, T.G., and Infante, D.M. (2017). Projected impacts of climate change on stream salmonids with implications for resilience-based management. *Ecology of Freshwater Fish*, 26(2), 190-204. <https://doi.org/10.1111/eff.12267>
- Carroll, M., Bolton, M., Owen, E., Anderson, G.Q.A., Mackley, E.K., Dunn, E.K., Furness, R.W. (2017). Kittiwake breeding success in the southern North Sea correlates with prior sandeel fishing mortality. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27(6), 1164–1175. <https://doi.org/10.1002/aqc.2780>
- Carroll, M.J., Butler, A., Owen, E., Ewing, S.R., Cole, T., Green, J.A. *et al.* (2015). Effects of sea temperature and stratification changes on seabird breeding success. *Climate Research*, 66(1), 75–89. <https://doi.org/10.3354/cr01332>
- Carvalho, L., McDonald, C., de Hoyos, C., Mischke, U., Phillips, G., Borics, G. *et al.* (2013). Sustaining recreational quality of European lakes: minimising the health risks from algal blooms through phosphorus control. *Journal of Applied Ecology*, 50(2), 315-323. <https://doi.org/10.1111/1365-2664.12059>
- Castelle, B., Dodet, G., Masselink, G., Scott, T. (2018). Increased Winter-Mean Wave Height, Variability, and Periodicity in the Northeast Atlantic Over 1949–2017. *Geophysical Research Letters*, 45(8), 3586-3596. <https://doi.org/10.1002/2017GL076884>
- CBD. (2020). Aichi Biodiversity Targets. Retrieved from <https://www.cbd.int/sp/targets/>
- CCC (2013) Managing the Land in a Changing Climate. Chapter 4: regulating Services – upland peat. Adaptation Sub-Committee. Retrieved from https://www.theccc.org.uk/wp-content/uploads/2013/07/ASC-2013-Book-singles_2.pdf
- CCC. (2017). Wine case study and Exotic Fruit Indicator. Retrieved from <https://www.theccc.org.uk/wp-content/uploads/2019/07/Outcomes-Wine-case-study.pdf>
- CCC. (2018a). Managing the coast in a changing climate. Retrieved from <https://www.theccc.org.uk/publication/managing-the-coast-in-a-changing-climate/>
- CCC. (2018b). Land use: Reducing emissions and preparing for climate change. Retrieved from <https://www.theccc.org.uk/publication/land-use-reducing-emissions-and-preparing-for-climate-change/>

- CCC. (2019a). Net Zero -The UK's contribution to stopping global warming. Retrieved from <https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/>
- CCC. (2019b). NAP2 Summary Report: 2019 Progress Report to Parliament. Retrieved from <https://www.theccc.org.uk/wp-content/uploads/2019/07/2019-Progress-Report-Summary.pdf>
- CCC. (2019c). Water Stress and Resilience. Retrieved from <https://www.theccc.org.uk/wp-content/uploads/2019/07/Outcomes-Water-stress-case-study.pdf>
- CCC. (2020). Land use: Policies for a Net Zero UK. Retrieved from <https://www.theccc.org.uk/publication/land-use-policies-for-a-net-zero-uk/>
- CCRA2. (2017). UK Climate Change Risk Assessment 2017 Evidence Report. Retrieved from <https://www.theccc.org.uk/uk-climate-change-risk-assessment-2017/>
- Centre for Economics and Business Research (2018). Feeling the heat. <https://cebr.com/reports/feeling-the-heat-extreme-weather-set-to-cost-uk-consumers-45-million-per-week/>
- Challies, E., Newig, J., Thaler, T., Kochskämper, E., and Levin-Keitel, M. (2016). Participatory and collaborative governance for sustainable flood risk management: An emerging research agenda. . *Environmental Science and Policy*, 55, 275– 280. Retrieved from <https://www.repo.uni-hannover.de/bitstream/handle/123456789/2095/Challies%20et%20al%202016,%20Participatory%20and%20Collaborative%20Governance%20for%20Sustainable%20Flood%20Risk%20Management.pdf;jsessionid=2CFC8AFDFCF2ED8A8B878FF143B7E8D8?sequence=1>
- Challinor, A. and Benton, T. (2021) International dimensions. In: *The Third UK Climate Change Risk Assessment Technical Report* [Betts, R.A., Haward, A.B. and Pearson, K.V. (eds.)]. Prepared for the Climate Change Committee, London <https://www.ukclimaterisk.org/independent-assessment-ccra3/technical-report/>
- Chamen, W.T., Moxey, A.P., Towers, W., Balana, B., Hallett, P.D. (2015). Mitigating arable soil compaction: A review and analysis of available cost and benefit data. *Soil and Tillage Research*, 146, 10-25. <https://doi.org/10.1016/j.still.2014.09.011>
- Chang, J., Viovy, N., Vuichard, N., Ciais, P., Campioli, M., Klumpp, K. *et al.* (2015). Modeled changes in potential grassland productivity and in grass-fed ruminant livestock density in Europe over 1961–2010. *PLoS ONE*, 10(5), e0127554. <https://doi.org/10.1371/journal.pone.0127554>
- Chapman, D. S., Gunn, I.D.M., Pringle, H.E.K., Siriwardena, G.M., Taylor, P., Thackeray, S.J. *et al.* (2020). Invasion of freshwater ecosystems is promoted by network connectivity to hotspots of human activity. *Global Ecology and Biogeography*, 29(4), 645 - 655. <https://doi.org/10.1111/geb.13051>
- Charlton, M.B., Bowes, M.J., Hutchins, M.G., Orr, H.G., Soley, R., Davison, P. (2018). Mapping eutrophication risk from climate change: future phosphorus concentrations in English rivers. *Science Total Environment*, 613-614, 1510-1526. <https://doi.org/10.1016/j.scitotenv.2017.07.218>
- Chen, X. L., Lewandowska, D., Armstrong, M.R., Baker, K., Lim, T-Y., Bayer, M. *et al.* (2018). Identification and rapid mapping of a gene conferring broad-spectrum late blight resistance in the diploid potato species *Solanum verrucosum* through DNA capture technologies. *Theoretical and Applied Genetics*, 131, 1287 – 1297. <https://doi.org/10.1007/s00122-018-3078-6>
- Cheung, W.W.L., Frölicher, T.L., Asch, R.G., Jones, M.C., Pinsky, M.L., Reygondeau, G. *et al.* (2016). Building Confidence in Projections of the Responses of Living Marine Resources to Climate Change. *ICES Journal of Marine Science*, 73(5), 1283–1296. <https://doi.org/10.1093/icesjms/fsv250>
- Chiabai, A., Quiroga, S., Martinez-Juarez. P., Higgins, S., Taylor, T. (2018). The nexus between climate change, ecosystem services and human health: Towards a conceptual framework. *Science of the Total Environment*, 635, 1191–1204. <https://doi.org/10.1016/j.scitotenv.2018.03.323>

- Christie, E.K., Spencer, T., Owen, D., McIvor, A.L., Möller, I., and Viavattene, C. (2017). Regional coastal flood risk assessment for a tidally dominant, natural coastal setting: North Norfolk, southern North Sea. *Coastal Engineering*, 134, 177–190. <https://doi.org/10.1016/j.coastaleng.2017.05.003>
- Cimato, F., Mullan, M. (2010). *Adapting to climate change: Analysing the role of Government*. Retrieved from London, UK: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69194/pb13341-analysing-role-government-100122.pdf
- Clark, S., Roques, S., Weightman, R., Kindred, D. (2016). *Understanding triticale. AHDB Report*. Retrieved from <https://projectblue.blob.core.windows.net/media/Default/Research%20Papers/Cereals%20and%20Oilseed/pr556-understanding-triticale.pdf>
- Clarke, D., Hess, T.M., Haro-Monteagudo, D., Semenov, M.A., Knox, J.W. (2021). Assessing future drought risks and wheat yield losses in England. *Agricultural and Forest Meteorology*, 297, 108248. <https://doi.org/10.1016/j.agrformet.2020.108248>
- Classen, A.T., Sundqvist, M.K., Henning, J.A., Newman, G.S., Moore, J.A., Cregger, M.A. *et al.* (2015). Direct and indirect effects of climate change on soil microbial and soil microbial-plant interactions: What lies ahead? *Ecosphere*, 6, 1 - 21. <https://doi.wiley.com/10.1890/ES15-00217.1>
- Cleasby, I.R., Owen, E., Wilson, L., Wakefield, E.D., O'Connell, P., Bolton, M. (2020). Identifying important at-sea areas for seabirds using species distribution models and hotspot mapping. *Biological Conservation*, 241, 108375. <https://doi.org/10.1016/j.biocon.2019.108375>
- Climate Coalition (2019). Recipe for Disaster. <https://www.theclimatecoalition.org/recipefordisaster>
- Climatechange. (2018). NB39 Freshwater habitats with reported presence of key invasive non-native species (INNS). Retrieved from https://www.climatechange.org.uk/media/3417/nb39_freshwater_inns_2018update_v02.pdf
- Climate Northern Ireland. (2019). *Civil Society and Local Government Adapts. Supporting document*. Retrieved from <https://www.daera-ni.gov.uk/publications/northern-ireland-climate-change-adaptation-programme-2019-2024>
- Coates, T., and Tapsell, S. (2019). Planning for an uncertain future: the challenges of a locally based collaborative approach to coastal development decisions. *Environmental Science & Policy*, 101, 24-31. <https://doi.org/10.1016/J.ENVSCI.2019.07.005>
- Cochrane, S.K.J., Andersen, J.H., Berg, T., Blanchet, H., Borja, A., Carstensen, J. *et al.* (2016). What Is Marine Biodiversity? Towards Common Concepts and Their Implications for Assessing Biodiversity Status. *Frontiers in Marine Science*. <https://doi.org/10.3389/fmars.2016.00248>
- Cohen-Shacham, E., Andrade, A., Dalton, J., Dudley, N., Jones, M., Kumar, C. *et al.* (2019). Core principles for successfully implementing and upscaling Nature-based Solutions. *Environmental Science & Policy*, 98, 20-29. <https://doi.org/10.1016/j.envsci.2019.04.014>
- Cohen-Shacham, E., Janzen, C.; Maginnis, S., Walters, G. (2016). Nature-based solutions to address global societal challenges. *IUCN*. <https://doi.org/10.2305/IUCN.CH.2016.13.en>
- Collins, Á.B., Barrett, D.J., Doherty, M.L., McDonnell, M., Mee, J.F. (2017). Significant re-emergence and recirculation of Schmallenberg virus in previously exposed dairy herds in Ireland in 2016. *Transbound Emerg Dis*, 12, 234. <https://doi.org/10.1111/tbed.12685>
- Collins, Á.B., Mee, J.F., Doherty, M.L., Barrett, D.J., and England, M.E. (2018). Culicoides species composition and abundance on Irish cattle farms: implications for arboviral disease transmission. *Parasites & Vectors*, 11, 472. <https://doi.org/10.1186/s13071-018-3010-6>

- Coolen, J.W., Van Der Welde, B., Cuperus, J., Blomberg, M., Van Moorsel, G.W., Faasse, M.A. et al. (2020). Benthic biodiversity on old platforms, young wind farms, and rocky reefs. *ICES Journal of Marine Science*, 77(3), 1250-1265. <https://doi.org/10.1093/icesjms/fsy092>
- Cooper, H.V., Sjögersten, S., Lark, R.M., and Mooney, S.J. (2021). To till or not to till in a temperate ecosystem? Implications for climate change mitigation. *Environmental Research Letters (Accepted manuscript)*. <https://doi.org/10.1088/1748-9326/abe74e>
- Cooper, J.A.G., O'Connor, M.C., Mclvor, S. (2016). Coastal Defences versus coastal ecosystem: a regional appraisal. *Marine Policy*. <https://doi.org/10.1016/j.marpol.2016.02.021>
- COREPOINT. (2007). Quantification of the economic benefits of natural coastal systems. Coastal Research and Policy Integration. COREPOINT - EU-Interreg IIIb project report. Retrieved from https://corepoint.ucc.ie/FinalDeliverables/Publications/Effectiveness_of_CurrentSpatialPolicies/Quantification%20of%20the%20economic%20benefits%20of%20natural%20coastal%20ecosystems.pdf
- Corstanje, R., Mercer, T.G., Rickson, J.R., Deeks, L.K., Newell-Price, P., Holman, I. et al. (2017). Physical soil quality indicators for monitoring British soils. *Solid Earth*, 8(5), 1003-1016. <https://doi.org/10.5194/se-8-1003-2017>
- Costa, H., de Rigo, D., Libertà, G., Houston Durrant, T., San-Miguel-Ayanz, J. (2020). European wildfire danger and vulnerability in a changing climate: towards integrating risk dimensions (978-92-76-16898-0). Retrieved from Luxembourg: <https://ec.europa.eu/jrc/en/publication/european-wildfire-danger-and-vulnerability-under-changing-climate-towards-integrating-risk>
- Cottier-Cook, E.J., Beveridge, C., Bishop, J.D.D., Brodie, J., Clark, P.F., Epstein, G. et al. (2017). Non-native species. *MCCIP Science Review 2017*, 47-61. <https://doi.org/10.14465/2017.arc10.005-nns>
- Creative Research. (2018). *Survey of Attitudes, Knowledge and Behaviour in Relation to Non-native Species. Report of findings*. Retrieved from <https://secure.fera.defra.gov.uk/nonnativespecies/downloadDocument.cfm?id=1709>.
- Crick, H.Q.P. Crosher, I.E., Mainstone, C.P., Taylor, S.D., Wharton, A., Langford, P. et al. (2020). Nature Networks Evidence Handbook. (Natural England Research Report NERR081). Retrieved from <http://publications.naturalengland.org.uk/publication/6105140258144256>
- Crowther, T.W., Todd-Brown, K.E., Rowe, C.W., Wieder, W.R., Carey, J.C., Machmuller, M.B. et al. (2016). Quantifying global soil carbon losses in response to warming. *Nature*, 540(7631), 104-108. <https://doi.org/10.1038/nature20150>
- Cunsolo, A., and Ellis, N.R. (2018). Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change*, 8(4), 275. <https://doi.org/10.1038/s41558-018-0092-2>
- DAERA. (2018a). Northern Ireland Water Framework Directive. Statistics Report. Retrieved from <https://www.daera-ni.gov.uk/sites/default/files/publications/daera/NIEA%20-%20WFD%20Statistics%20Report%202018.pdf>
- DAERA. (2018b). Delivering Our Future, Valuing Our Soils: A Sustainable Agricultural Land Management Strategy for Northern Ireland. Retrieved from <https://www.daera-ni.gov.uk/sites/default/files/publications/daera/16.17.079%20Sustainable%20Land%20Management%20Strategy%20final%20amended.PDF>
- DAERA. (2019a). Baseline Study and Gap Analysis of Coastal Erosion Risk Management in N Ireland. Retrieved from <https://www.infrastructure-ni.gov.uk/sites/default/files/publications/infrastructure/coastal-erosion-risk-management-report-2019.pdf>

- DAERA. (2019b). Northern Ireland Climate Change Adaptation Programme 2019-2024. Retrieved from <https://www.daera-ni.gov.uk/publications/northern-ireland-climate-change-adaptation-programme-2019-2024>
- Dahlke, F.T., Wohlrab, S., Butzin, M., Pörtner, H.O. (2020). Thermal bottlenecks in the life cycle define climate vulnerability of fish. *Science*, 369(6499), 65-70. <https://doi.org/10.1126/science.aaz3658>
- Dancy, S., Skelsey, P., Cooke, D. (2017). The Hutton Criteria: a classification tool for identifying high risk period for potato late blight disease development in Great Britain. (16th Euroblight Workshop Special Report 18). Retrieved from The James Hutton Institute, Invergowrie, Dundee DD2 5DA Scotland: https://euroblight.net/fileadmin/euroblight/Workshops/Aarhus/Proceedings/5_Siobhan_Dancy_p53-58.pdf
- Danovaro, R. Corinaldesi, C., Dell'Anno, A., Fuhrman, J.A., Middelburg, J.J., Noble, R. T., and Suttle, C.A. (2011). Marine viruses and global climate change. *FEMS microbiology reviews*, 35(6), 993-1034. <https://doi.org/10.1111/j.1574-6976.2010.00258.x>
- Dasgupta, P. (2021). The Economics of Biodiversity: The Dasgupta Review. Retrieved from <https://www.gov.uk/government/publications/final-report-the-economics-of-biodiversity-the-dasgupta-review>
- Davies, G.M., and Legge, C.J. (2016). Regional variation in fire weather controls the reported occurrence of Scottish wildfires. *PeerJ*, 4, e2649. <https://doi.org/10.7717/peerj.2649>
- Davies, J.G., Humphreys, E.M., Pearce-Higgins, J.W. (2020). Projected future vulnerability of seabirds within the INTERREG VA area to climate change. MarPAMM Project report. Retrieved from <https://www.mpa-management.eu/>
- Dawson, R.J., Nicholls, R.J., and Day, S. (2015). The challenge for coastal management during the third millennium. In *Broad Scale Coastal Simulation: New Techniques to Understand and Manage Shorelines in the Third Millennium* (Vol. 49, pp. 1-78): Springer Netherlands. https://doi.org/10.1007/978-94-007-5258-0_1
- Dawson, T., Hambly, J., Kelley, A., Lees, W., Miller, S. (2020). Coastal heritage, global climate change, public engagement, and citizen science. *Proceedings of the National Academy of Sciences*, 117(15), 8280-8286. <https://doi.org/10.1073/pnas.1912246117>
- Day, S.A., O'Riordan, T., Bryson, J., Frew, P., Young, R. (2015). Many Stakeholders, Multiple Perspectives: Long-Term Planning for a Future Coast. In Nicholls, R., Dawson, R, Day, S. (Ed.), *Broad Scale Coastal Simulation. Advances in Global Change Research* (Vol. 49). https://doi.org/10.1007/978-94-007-5258-0_12
- de Boer, J.G., and Harvey, A. (2020). Range-Expansion in Processionary Moths and Biological Control. *Insects*, 11(5), 267. <https://doi.org/10.3390/insects11050267>
- de Castro Júnior, S. L., and da Silva, I.J.O. (2021). The specific enthalpy of air as an indicator of heat stress in livestock animals. *International Journal of Biometeorology* 65, 149–161. <https://doi.org/10.1007/s00484-020-02022-8>
- De Jong, M.C., Wooster, M.J., Kitchen, K., Manley, C., and Gazzard, R. (2016). Calibration and evaluation of the Canadian Forest fire weather index (FWI) system for improved wildland fire danger rating in the UK. *Nat. Hazards Earth Syst. Sci. Discuss*, 3, 6997-7051. Retrieved from <https://nhess.copernicus.org/preprints/3/6997/2015/nhessd-3-6997-2015.pdf>
- De Palma, A., Dennis, R.L., Brereton, T., Leather, S.R., and Oliver, T.H. (2017). Large reorganizations in butterfly communities during an extreme weather event. *Ecography*, 40(5), 577-585. <https://doi.org/10.1111/ecog.02228>

- De Vries, F. Griffiths, R.I., Bailey, M., Graig, H., Girlanda, M., Gweon, H.S. *et al.* (2018). Soil bacterial networks are less stable under drought than fungal networks. *Nature Communications* 9(3033). <https://dx.doi.org/10.1038%2Fs41467-018-05516-7>
- De Vries, F.T., Liiri, M.E., Bjørnlund, L., Bowker, M.A., Christensen, S., Setälä, H.M. Bardgett, R.D. (2012). Land use alters the resistance and resilience of soil food webs to drought. *Nature Climate Change*, 2, 276–280. <https://doi.org/10.1038/nclimate1368>
- Defra. (2009). Safeguarding our soils – A strategy for England. Retrieved from <https://www.gov.uk/government/publications/safeguarding-our-soils-a-strategy-for-england>
- Defra. (2014). The consequences of climate change for the water environment in England: an assessment of the current evidence: Final report WT1540. 69pp. Retrieved from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwim3dqwio_wAhXBC-wKHbl5DhwQFjADegQIEhAD&url=http%3A%2F%2Fsciencesearch.defra.gov.uk%2FDocument.aspx%3FDocument%3D12328_WT1540ConsequencesofCCforthewaterenvironmentinEn
- Defra. (2015). Impact assessment. River basin management plans: impact assessment. Retrieved from <https://www.gov.uk/government/publications/river-basin-management-plans-impact-assessment>
- Defra. (2017) Risk assessment for Bluetongue Virus (BTV-8): risk assessment of entry into the United Kingdom Updated Qualitative Risk Assessment. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/714604/qra-BTV8-170526.pdf
- Defra. (2018a). The National Adaptation Programme and the Third Strategy for Climate Adaptation Reporting. Making the country resilient to a changing climate. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/727252/national-adaptation-programme-2018.pdf
- Defra. (2018b). National Pollinator Strategy: Implementation Plan, 2018-2021. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/912826/nps-implementation-plan-2018-2021.pdf
- Defra. (2018c). Tree Health Resilience Strategy Building the resilience of our trees, woods and forests to pests and diseases. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/710719/tree-health-resilience-strategy.pdf
- Defra. (2019a) Agriculture in the United Kingdom 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/848641/AUK_2018_09jul19a.pdf
- Defra. (2019b) Bluetongue virus (BTV-8) in Germany and Belgium. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/818686/uoa-btv8-germany-belgium-update4.pdf
- Defra (2019c). Marine Strategy Part One: UK updated assessment and Good Environmental Status. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/921262/marine-strategy-part1-october19.pdf
- Defra. (2020a). UK Biodiversity Indicators 2020. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/926506/UKBI-2020-A.pdf.

- Defra. (2020b). Wild Bird populations in the UK, 1986 to 2018. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877998/UK_Wild_birds_1970-2018_final_accessv2.pdf
- Defra. Scottish and Welsh Governments. (2015). The Great Britain invasive non-native species strategy. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/455526/gb-non-native-species-strategy-pb14324.pdf
- Defra. UK Plant Health Risk Register. Retrieved from <https://secure.fera.defra.gov.uk/phiw/riskRegister/>
- Dellar, M., Topp, C.F.E., Banos, G., Wall, E. (2018). A meta-analysis on the effects of climate change on the yield and quality of European pastures. *Agriculture, Ecosystems & Environment*, 265, 413–420. <https://doi.org/10.1016/j.agee.2018.06.029>
- den Herder, M., Moreno, G., Mosquera-Losada, R.M., Palma, J.H.N., Sidiropoulou, A., Santiago-Freijanes, J.J. *et al.* (2017). Current extent and stratification of agroforestry in the European Union. *Agriculture Systems & Environment*, 241, 121-132. <https://doi.org/10.1016/j.agee.2017.03.005>
- Dennett, A.L., and Trethowan, R.M. (2013). Milling efficiency of triticale grain for commercial flour production. *Journal of Cereal Science*, 57, 527-530. <https://doi.org/10.1016/j.jcs.2013.03.002>
- Dennis, E.B., Brereton, T.M., Morgan, B.J.T., Fox, R., Shortall, C.R., Prescott, T., Foster, S. (2019). Trends and indicators for quantifying moth abundance and occupancy in Scotland. *Journal of Insect Conservation*, 23, 369-380. <https://doi.org/10.1007/s10841-019-00135-z>
- Di Gregorio, M.; Nurrochmat, D.R.; Paavola, J.; Sari, L.; Fatorelli, I.M.L.; Pramova, E.B.; Locatelli, B.; Brockhaus, M.; Kusumadewi, S.D. (2017). Climate policy integration in the land use sector: mitigation, adaptation and sustainable development linkages. *Environmental Science and Policy*, 67, 35-43. <https://doi.org/10.1016/j.envsci.2016.11.004>
- Dittrich, R., Wreford, A., Topp, C.F.E., Eory, V., and Moran, D. (2017). A guide towards climate change adaptation in the livestock sector: adaptation options and the role of robust decision-making tools for their economic appraisal *Regional Environmental Change*, 17, 1701-1712. <https://doi.org/10.1007/s10113-017-1134-4>
- Dobel, A.J., O'Hare, M., Gunn, I., Edwards, F. (2019). Streams and Rivers Report Card. Retrieved from https://aboutdrought.info/wp-content/uploads/2019/10/AboutDrought-ReportCard-RIVERS_STREAMS_DRAFTS.pdf
- Dodd, R.J., Chadwick, D.R., Harris, I.M., Hines, A., Hollis, D., Economou, T. *et al.* (2020). Spatial co-localisation of extreme weather events: a clear and present danger. *Ecology Letters (Early view)*. <https://doi.org/10.1111/ele.13620>
- Doick, K.J., Peace, A., Hutchings, T.R. (2014). The role of one large greenspace in mitigating London's nocturnal urban heat island. *Science Total Environment*, 493, 662-671. <https://doi.org/10.1016/j.scitotenv.2014.06.048>
- Donnelly, A. (2018). Climate change: potential implications for Ireland's biodiversity. *International Journal of Biometeorology*, 62, 1221–1228. <https://doi.org/10.1007/s00484-018-1526-2>
- Donnelly, A., Yu, R., Liu, L. (2015). Trophic-level responses differ as climate warms in Ireland. *International Journal for Biometeorology*, 59(8), 1007–1017. <https://doi.org/10.1007/s00484-014-0914-5>
- Donnison, C., Holland, R.A., Hastings, A., Armstrong, L.M., Eigenbrod, F., Taylor, G. (2020). Bioenergy with Carbon Capture and Storage (BECCS): Finding the win–wins for energy, negative emissions and ecosystem services—size matters. *GCB Bioenergy*, 12(8), 586-604. <https://doi.org/10.1111/gcbb.12695>

- Duffield, S.J., Lee Bas, B., Morecroft, M.D. (2021). Climate change vulnerability and the state of adaptation on England's National Nature Reserves. *Biological Conservation*, 254, 108938
<https://doi.org/10.1016/j.biocon.2020.108938>
- Duignan, P.J., Van Bresseem, M.F., Baker, J.D., Barbieri, M., Colegrove, K.M., De Guise, S. *et al.* (2014). Phocine distemper virus: current knowledge and future directions. *Viruses*, 6(12), 5093–5134.
<https://doi.org/10.3390/v6125093>
- Dunn, R.J.H., Mead, N.E., Willett, K.M., Parker, D.E. (2014). Analysis of heat stress in UK dairy cattle and impact on milk yields. *Environmental Research Letters*, 9(6). <https://doi.org/10.1088/1748-9326/9/6/064006>
- Dutta, P., Chakraborti, S., Chaudhuri, K.M., Mondal, S. (2020). Physiological Responses and Resilience of Plants to Climate Change. In Rakshit, A., Singh, H., Singh, A, Singh, U., Fraceto, L. (eds). *New Frontiers in Stress Management for Durable Agriculture*. https://doi.org/10.1007/978-981-15-1322-0_1
- Dye, S., Berx, B., Opher, J., Tinker, J.P., Renshaw, R. (2020). Climate change and salinity of the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 76–102.
<https://doi.org/10.14465/2020.arc04.sal>
- EA. (2007). *The total environmental costs and benefits of agriculture in the UK*. Retrieved from Bristol. Available from the Environment Agency on request.
- EA. (2015). Impact assessment for the updated river basin management plans (2015): evidence base. Retrieved from
[https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/470925/Impact assessment update to the RBMPs for England s water environment 2015 .pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/470925/Impact_assessment_update_to_the_RBMPs_for_England_s_water_environment_2015_.pdf)
- EA. (2016). Restoration measures to improve river habitats during low flows (SC120050/R). Retrieved from
[https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/552341/Restoration measures to improve river habitats during low flows - report.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/552341/Restoration_measures_to_improve_river_habitats_during_low_flows_-_report.pdf)
- EA. (2017a). Delivering sustainable river basin management: plausible future scenarios for the water environment to 2030 and 2050 (Report C: Implications). Retrieved from
[https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/704292/Future water scenarios report C - implications.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/704292/Future_water_scenarios_report_C_-_implications.pdf)
- EA. (2017b). Plausible future scenarios for the water environment to 2030 and 2050 - Project summary. Retrieved from
[https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/650327/Plausible future scenarios for the water environment to 2030 and 2050 - summary.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/650327/Plausible_future_scenarios_for_the_water_environment_to_2030_and_2050_-_summary.pdf)
- EA. (2018a). Working with natural processes to reduce flood risk (SC150005/S). Retrieved from
<https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk>
- EA. (2018b). Working with Natural Processes – Evidence Directory. Retrieved from
[https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/681411/Working with natural processes evidence directory.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/681411/Working_with_natural_processes_evidence_directory.pdf)
- EA. (2018). National Review of Statutory Habitat Creation associated with Flood and Coastal Risk Management Activity. Progress Report. Available on request from EA
- EA. (2019a). State of the Environment: Soils. Retrieved from
[https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/805926/State of the environment soil report.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/805926/State_of_the_environment_soil_report.pdf)

- EA. (2019b). State of the Environment: Water Quality. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/709493/State_of_the_environment_water_quality_report.pdf
- EA. (2019c). Climate change and eutrophication risk thresholds in English rivers (SC140013/R2 (Submitted evidence). Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/822910/Climate_change_and_eutrophication_risk_in_English_rivers_-_report.pdf
- EA. (2019d). 2021 River Basin Management Plan. The Climate Crisis. River basin planning: Challenges and Choices consultation. Retrieved on https://consult.environment-agency.gov.uk/environment-and-business/challenges-and-choices/user_uploads/climate-crisis-rbmp-2021.pdf
- EA. (2020). National Flood and Coastal Erosion Risk Management Strategy for England. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/920944/023_15482_Environment_agency_digitalAW_Strategy.pdf
- Earlie, C., Masselink, G., and Russell, P. (2018). The role of beach morphology on coastal cliff erosion under extreme waves. *Earth Surface Processes and Landforms*, 43(6), 1213-1228. <https://doi.org/10.1002/esp.4308>
- ECONADAPT (2017). Review of the Costs and benefits of adaptation. Report of the EC RTD Economics of Adaptation Project. Available at <https://econadapt.eu/sites/default/files/docs/Econadapt-policy-report-on-costs-and-benefits-of-adaptaiton-july-draft-2015.pdf>.
- Ecosulis and Farmlytics. (2019). *The Economic Impact of Extreme Weather on Scottish Agriculture. Consultancy Report*. Retrieved from <https://www.wwf.org.uk/sites/default/files/2019-04/Impact%20of%20extreme%20weather%20on%20Scottish%20Farmers%202018%20FINAL.pdf>
- Edeline, E., Groth, A., Cazelles, B., Claessen, D., Winfield, I., Ohlberger, J. *et al.* (2016). Pathogens trigger top-down climate forcing on ecosystem dynamics. *Oecologia*, 181, 519-532. <https://doi.org/10.1007/s00442-016-3575-8>
- Edmondson, J.L., Stott, I., Davies, Z.G., Gaston, K.J., Leake, J.R. (2016). Soil surface temperatures reveal moderation of the urban heat island effect by trees and shrubs. *Science Reports*, 6. <https://doi.org/10.1038/srep33708>
- EFTEC. (2014). Valuing the UK Marine Environment – an Exploratory Study of Benthic Ecosystem Services. Retrieved from London, UK: http://sciencesearch.defra.gov.uk/Document.aspx?Document=12388_ME5106ValuingtheUKMarineEnvironment-FinalReport.pdf
- Eigenbrod, F., Gonzalez, P., Dash, J., Steyl, I. (2015). Vulnerability of ecosystems to climate change moderated by habitat intactness. *Global Change Biology*, 21, 275-286. <https://doi.org/10.1111/gcb.12669>
- Elliott, J.A., Henrys, P., Tanguy, M., Cooper, J., Maberly, S.C. (2015). Predicting the habitat expansion of the invasive roach *Rutilus rutilus* (Actinopterygii, Cyprinidae), in Great Britain. *Hydrobiologia*, 751(1), 127-134. <https://doi.org/10.1007/s10750-015-2181-9>
- Elliott, J.A., McElarney, Y.R., Allen, M. (2016). The past and future of phytoplankton in the UK's largest lake, Lough Neagh. *Ecological Indicators*, 68, 142-149. <http://dx.doi.org/10.1016/j.ecolind.2015.07.015>
- Elliott, J.M., and Elliot, J.A. (2010). Temperature requirements of Atlantic salmon *Salmo salar*, brown trout *Salmo trutta* and Arctic charr *Salvelinus alpinus*: predicting the effects of climate change. *Journal of Fish Biology*, 77(8), 1793-1817. <https://doi.org/10.1111/j.1095-8649.2010.02762.x>

- Ellis, C.J. (2015). Ancient woodland indicators signal the climate change risk for dispersal-limited species. *Ecological Indicators*, 53,106–114. <https://www.sciencedirect.com/science/article/pii/S1470160X15000527?via%3Dihub>
- Emmanuel, R., Loconsole, A. (2015). Green infrastructure as an adaptation approach to tackling urban overheating in the Glasgow Clyde Valley Region. *Landscape Urban Planning*, 138, 71-86. <https://doi.org/10.1016/j.landurbplan.2015.02.012>
- Emmett, B.E., and the GMEP team. (2017). Glastir Monitoring & Evaluation Programme. Final Report to Welsh Government (CEH Project no. C04780, C05371, C05782). Retrieved from <http://nora.nerc.ac.uk/id/eprint/518194/>
- Ennos, R., Cottrell, J., Hall, J., O'Brien, D. (2019). Is the introduction of novel exotic forest tree species a rational response to rapid environmental change? – A British perspective. *Forest Ecology and Management*, 432, 718 - 728. <http://dx.doi.org/10.1016/j.foreco.2018.10.018>
- Entwistle, N.S., Heritage, G.L., Schofield, L.A., and Williamson, R.J. (2019). Recent changes to floodplain character and functionality in England. *Catena*, 174, 490-498. <https://doi.org/10.1016/j.catena.2018.11.018>
- Environmental Audit Committee. (2016). Soil Health. Retrieved from <https://publications.parliament.uk/pa/cm201617/cmselect/cmenvaud/180/180.pdf>
- Environmental Audit Committee. (2019). Inquiry on Invasive Species. Retrieved from <https://publications.parliament.uk/pa/cm201919/cmselect/cmenvaud/88/8804.htm>
- Eriksson, L., Boberg, J., Cech, T.L., Corcobado, T., Desprez-Loustau, M-L., Hietala, A.M. *et al.* (2019). Invasive forest pathogens in Europe: Cross-country variation in public awareness but consistency in policy acceptability. *Ambio*, 48, 1–12. <https://doi.org/10.1007/s13280-018-1046-7>
- Essl, F. *et al.* (2015). Crossing Frontiers in Tackling Pathways of Biological Invasions. *BioScience*, 65, 769–782. <https://doi.org/10.1093/biosci/biv082>
- Esteves, L.S., and Thomas, K. (2014). Managed realignment in practice in the UK: results from two independent surveys. *Journal of Coastal Research* 70, 407–413. <https://doi.org/10.2112/SI70-069.1>
- European Commission. (2013). Climate change adaptation, coastal and marine issues. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. Commission staff working document. Retrieved from <https://op.europa.eu/en/publication-detail/-/publication/e25a61b2-6e51-43d7-aa8d-c41d48599dd1/language-en/format-PDF/source-120600022>
- European Commission. (2017). Study on the economic benefits of Marine Protected Areas Literature review analysis. Written by ICF Consulting Services Limited, in association with IEEP and PML, September. <https://op.europa.eu/en/publication-detail/-/publication/dbe3d250-b0b5-11e8-99ee-01aa75ed71a1>
- EUROSION (2004). EUROSION portal. <http://www.euroSION.org>
- Evans, C., Artz, R., Moxley, J., Smyth, M-A., Taylor, E., Archer, N. *et al.* (2017). Implementation of an emission inventory for UK peatlands. Retrieved from Centre for Ecology and Hydrology, Bangor: https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1904111135_UK_peatland_GHG_emissions.pdf
- Evans, P.G.H., and Waggitt, J.J. (2020). Impacts of climate change on marine mammals, relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 421–455. <https://doi.org/10.14465/2020.arc19.mmm>
- Everall, N.C., Johnson, M.F., Wilby, R.L., Bennett, C.J. (2015). Detecting phenology change in the mayfly *Ephemera danica*: responses to spatial and temporal water temperature variations. *Ecological Entomology*, 40, 95-105. <https://doi.org/10.1111/een.12164>

- Expert Working Group. (2020). Delivering Our Future, Valuing Our Soils: A Sustainable Agricultural Land Management Strategy for Northern Ireland. Retrieved from <https://www.daera-ni.gov.uk/publications/sustainable-agricultural-land-management-strategy-report-and-executive-summary>
- Fady, B., Cottrell, J., Ackzell, L., Alía, R., Muys, B., Prada, A. *et al.* (2016). Forests and global change: what can genetics contribute to the major forest management and policy challenges of the twenty-first century? *Regional Environmental Change* 16, 927–939. <https://doi.org/10.1007/s10113-015-0843-9>
- Faillietaz, R., Beaugrand, G., Goberville, E., Kirby, R.R. (2019). Atlantic Multidecadal Oscillations drive the basin-scale distribution of Atlantic bluefin tuna. *Science advances*, 5(1), eaar6993. <https://doi.org/10.1126/sciadv.aar6993>
- Falloon, P., Bebber, D., Bryant, J., Bushell, M., Challinor, A.J., Dessai, S. *et al.* (2015). Using climate information to support crop breeding decisions and adaptation in agriculture. *World Agriculture*, 5(1), 25-42 Retrieved from https://www.researchgate.net/publication/279476205_Using_climate_information_to_support_crop_breeding_decisions_and_adaptation_in_agriculture
- Falloon, P., Challinor, A.J., Dessai, S., Hoang, L., Johnson, J., Koehler, A. (2014). Ensembles and uncertainty in climate change impacts. *Frontiers in Environmental Science*. <https://doi.org/10.3389/fenvs.2014.00033>
- Falloon, P.D., Soares, M.B., Manzanos, R., San-Martin, D., Liggins, F., Taylor, I. *et al.* (2018). The Land Management Tool: developing a climate service in Southwest UK. *Climate Services*, 9, 86-100. <https://doi.org/10.1016/j.cliser.2017.08.002>
- FAO. (2019). Decision-making and economics of adaptation to climate change in the fisheries and aquaculture sector. FAO Fisheries and Aquaculture Technical Paper No. 650. Retrieved from <http://www.fao.org/3/ca7229en/ca7229en.pdf>
- Feld, C.K., Fernandes, M.R., Ferreira, M.T., Hering, D., Ormerod, S.J., Venohr, M. *et al.* (2018). Evaluating riparian solutions to multiple stressor problems in river ecosystems—a conceptual study. *Water Research*, 139, 381-394. <https://doi.org/10.1016/j.watres.2018.04.014>
- Fennell, J., Geris, J., Wilkinson, M.E., Daalmans, R., and Soulsby, C. (2020). Lessons from the 2018 drought for management of local water supplies in upland areas: a tracer-based assessment. *Hydrological Processes* 34, 4190-4210. <https://doi.org/10.1002/hyp.1386>
- Fernandes, J.A., Frölicher, F., T.L., Rutterford, L.A., Erauskin-Extramiana, M., Cheung, W.W.L. (2020). Changes of potential catches for North-East Atlantic small pelagic fisheries under climate change scenarios. *Regional Environmental Change* 20, 116. <https://www.x-mol.com/paperRedirect/1310730126366052352>
- Fernandes, J.A., Papathanasopoulou, E., Hattam, C., Queirós, A.M., Cheung, W.W.W.L., Yool, A. *et al.* (2017). Estimating the Ecological, Economic and Social Impacts of Ocean Acidification and Warming on UK Fisheries. *Fish and Fisheries*, 18(3). <https://doi.org/10.1111/faf.12183>
- Fernando, N., Panozzo, J., Tausz, M., Norton, R., Fitzgerald, G., Khan, A., Seneweera, S. (2015). Rising CO2 concentration altered wheat grain proteome and flour rheological characteristics. *Food Chemistry*, 170, 448-454. <https://doi.org/10.1016/j.foodchem.2014.07.044>
- Ferreira, J.G., Hawkins, A.J.S., Monteiro, P., Moore, H., Service, M., Pascoe, P.L. *et al.* (2008). Integrated assessment of ecosystem-scale carrying capacity in shellfish growing areas. *Aquaculture*, 275(1-4), 138-151. <https://doi.org/10.1016/j.aquaculture.2007.12.018>

- Ferretto, A., Brooker, R., Aitkenhead, M., Matthews, R., Smith, P. (2019). Potential carbon loss from Scottish peatlands under climate change. *Regional Environmental Change*, 19(7), 2101-2111. <https://doi.org/10.1007/s10113-019-01550-3>
- Firkins, I. (1993). *Environmental tolerances of three species of freshwater crayfish*. Ph.D. thesis, University of Nottingham. Retrieved from <http://eprints.nottingham.ac.uk/11282/1/357927.pdf> (1)
- Fitton, J.M., Hansom, J.D., Rennie, A.F. (2016). A national coastal erosion susceptibility model for Scotland, Ocean & Coastal Management. *Ocean & Coastal Management*, 132, 80-89. <http://dx.doi.org/10.1016/j.ocecoaman.2016.08.018>
- Fobert, E., Zieba, G., Vilizzi, L., Godard, M.J., Fox, M.G., Stakėnas, S., Copp, G.H. (2013). Predicting non-native fish dispersal under conditions of climate change: case study in England of dispersal and establishment of pumpkinseed *Lepomis gibbosus* in a floodplain pond. *Ecology of Freshwater Fish* 22, 106–116. <https://doi.org/10.1111/eff.12008>
- Fodor, N., Foskolos, A., Topp, C.F.E., Moorby, J.M., Pásztor, L., Foyer, C.H. (2018). Spatially explicit estimation of heat stress-related impacts of climate change on the milk production of dairy cows in the United Kingdom. *PLoS ONE*, 13, e0197076. <https://doi.org/10.1371/journal.pone.0197076>
- Fones, H.N., Bebbler, D.P., Chaloner, T.M., Kay, W.T., Steinberg, G., Gurr, S.J. (2020). Threats to global food security from emerging fungal and oomycete crop pathogens. *Nature Food*, 1, 455 - 456. <https://doi.org/10.1038/s43016-020-0075-0>
- Fones, H., and Gurr, S. (2015). The impact of *Septoria tritici* Blotch disease on wheat: An EU perspective. *Fungal Genet Biol* 79, 3-7. <https://doi.org/10.1016/j.fgb.2015.04.004>
- Food, Farming and Countryside Commission. (2021). Farming for Change: Mapping a Route to 2030. Retrieved from <https://ffcc.co.uk/library/farmingforchangereport>
- Ford, H., Garbutt, A., Ladd, C., Malarkey, J., and Skov, M.W. (2016). Soil stabilization linked to plant diversity and environmental context in coastal wetlands. *Journal of Vegetation Science*, 27(2), 259-268. <https://doi.org/10.1111/jvs.12367>
- Forestry Commission Scotland (2014). Scotland's Native Woodlands. Results from the Native Woodland Survey of Scotland. Retrieved from <https://forestry.gov.scot/forests-environment/biodiversity/native-woodlands/native-woodland-survey-of-scotland-nwss>
- Forest Research. (2021a). *Great spruce bark beetle (Dendroctonus micans)*. Retrieved from <https://www.forestresearch.gov.uk/tools-and-resources/pest-and-disease-resources/great-spruce-bark-beetle-dendroctonus-micans/>
- Forest Research. (2021b). *Larger eight-toothed European spruce bark beetle (Ips typographus)*. Retrieved from <https://www.forestresearch.gov.uk/tools-and-resources/pest-and-disease-resources/larger-eight-toothed-european-spruce-bark-beetle-ips-typographus/>
- Forest Research. <https://www.forestresearch.gov.uk/tools-and-resources/fthr/pest-and-disease-resources/oak-processionary-moth-thaumetopoea-processionea/>
- Forest Research. <https://www.forestresearch.gov.uk/tools-and-resources/fthr/pest-and-disease-resources/ash-dieback-hymenoscyphus-fraxineus/>
- Forest Research. <https://www.forestresearch.gov.uk/tools-and-resources/fthr/pest-and-disease-resources/phythopthora-austrocedri/>
- Forest Research. <https://www.forestresearch.gov.uk/tools-and-resources/pest-and-disease-resources/>
- Forestry Commission. (2020a). Forestry Commission Key Performance Indicators. September 2020. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936074/FC_Headline_Key_Performance_Indicators_30Sep20.pdf

- Forestry Commission. (2020b). Managing England's woodlands in a climate emergency. Version 2: March 2020. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/872285/Climate_Change_Full_Guide.pdf
- Fox, L., Stukins, S., Hill, T., Miller, C.G. (2020). Quantifying the effect of anthropogenic climate change on calcifying plankton. *Scientific Reports*, 10(1), 1620. <https://doi.org/10.1038/s41598-020-58501-w>
- Fox, N.J., Smith, L.A., Houdijk, J.G.M., Athanasiadou, S., Hutchings, M.R. (2018). Ubiquitous parasites drive a 33% increase in methane yield from livestock. *International Journal for Parasitology*, 48(13), 1017-1021. <https://doi.org/10.1016/j.ijpara.2018.06.001>
- Fox, R., Oliver, T.H., Harrower, C., Parsons, M.S., Thomas, C.D., Roy, D.B. (2014). Long-term changes to the frequency of occurrence of British moths are consistent with opposing and synergistic effects of climate and land-use changes. *Journal of Applied Ecology*, 51(4), 949 - 957. <https://doi.org/10.1111/1365-2664.12256>
- Franke, J., Müller, C., Elliott, J., Ruane, A.C., Jagermeyr, J., Balkovic, J. *et al.* (2019). The GGCM Phase II experiment: global gridded crop model simulations under uniform changes in CO₂, temperature, water, and nitrogen levels (protocol version 1.0). *Geoscientific Model Development*. <https://doi.org/10.5194/gmd-2019-237>
- Franke, J., Müller, C., Elliott, J., Ruane, A.C., Jagermeyr, J., Balkovic, J. *et al.* (2020). Emulating the GGCM Phase II experiment: global gridded emulators of crop model responses to changes in CO₂, temperature, nitrogen, and water. *Geoscientific Model Development*, 13(5), 2315-2336. <https://doi.org/10.5194/gmd-13-2315-2020>
- Free, C.M., Thorson, J.T., Pinsky, M.L., Oken, K.L., Wiedenmann, J., Jensen, O.P. (2019). Impacts of historical warming on marine fisheries production. *Science*, 363, 979-983. <https://doi.org/10.1126/science.aau1758>
- Freer-Smith, P., and Webber, J. (2015). Tree pests and diseases: the threat to biodiversity and the delivery of ecosystem services. *Biodiversity and Conservation*, 26(13), 1–15. <https://doi.org/10.1007/s10531-015-1019-0>
- Friggens, N.L., Hester, A.J., Mitchell, R.J., Parker, T.C., Subke, J.A., and Wookey, P.A. (2020). Tree planting in organic soils does not result in net carbon sequestration on decadal timescales. 26(9), 5178-5188. <https://doi.org/10.1111/gcb.15229>
- Frontier Economics, Irbaris LLP and Ecofys UK. (2013). The Economics of Climate. Agriculture and Forestry Theme Report March 2013. Report to Defra and the Devolved administrations. March 2013. Available at <http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=18016>. Accessed April 2021.
- Frontier Economics, Irbaris, Ecofys. (2013). Economics of Climate Resilience Natural Environment Theme: Sea FishCA0401. Report to Defra and the Devolved Administrations. Retrieved from <http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=18016>
- Frost, M., Bayliss-Brown, G., Buckley, P., Cox, M., Dye, S., Sanderson, W. *et al.* (2016). A Review of Climate Change and the Implementation of Marine Biodiversity Legislation in the United Kingdom. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26(3), 576–595. <https://doi.org/10.1002/aqc.2628>
- Frost, T., Calbrade, N.A., Birtles, G.A., Mellan, H.J., Hall, C., Robinson, A.A. *et al.* (2020). Waterbirds in the UK 2018/19: The Wetland Bird Survey. Retrieved from British Trust for Ornithology, Thetford:

<https://www.bto.org/our-science/projects/wetland-bird-survey/publications/webs-annual-report/waterbirds-in-the-uk>

Futurecoast (2002) Futurecoast: Final Project Report. DEFRA.

http://www.coastalwiki.org/wiki/FUTURECOAST_project, UK

Gadanakis, Y., Bennett, R., Park, J., Areal, F.J. (2015). Improving productivity and water use efficiency: A case study of farms in England. *Agric. Water Management*, 160, 22–32.

<https://doi.org/10.1016/j.agwat.2015.06.020>

Gaines, S.D., Costello, C., Owashi, B., Mangin, T., Bone J., García Molinos, J. (2018). Improved fisheries management could offset many negative effects of climate change. *Science advances*, 4(8), eaao1378. <https://doi.org/10.1126/sciadv.aao1378>

Gallagher, J.N., and Biscoe, P.V. (1978). Radiation absorption, growth and yield of cereals. *The Journal of Agricultural Science*, 91(1), 47-60. <https://doi.org/10.1017/S0021859600056616>

Gallagher, J.N., and Biscoe, P.V., Hunter, B. (1976). Effects of drought on grain growth. *Nature*, 264(5586), 541-542. <https://doi.org/10.1038/264541a0>

Gallardo, B., and Aldridge, D.C. (2013). The ‘dirty dozen’: socio-economic factors amplify the invasion potential of 12 high risk aquatic invasive species in Great Britain and Ireland. *Journal of Applied Ecology*, 50, 757–766. <https://doi.org/10.1111/1365-2664.12079>

Gallardo, B., and Aldridge, D.C. (2013b). Evaluating the combined threat of climate change and biological invasions on endangered species. *Biological Conservation*, 160, 225–233.

<http://dx.doi.org/10.1016/j.biocon.2013.02.001>

Gallardo, B., and Aldridge, D.C. (2015). Is Great Britain heading for a ponto–caspien invasional meltdown? *Journal of Applied Ecology*, 52(1), 41-49. <https://doi.org/10.1111/1365-2664.12348>

Gallardo, B., and Aldridge, D.C. (2018). Inter-basin water transfers and the expansion of aquatic invasive species. *Water Research*, 143, 282-291. <https://doi.org/10.1016/j.watres.2018.06.056>

Gallardo, B., and Aldridge, D.C. (2020). Priority setting for invasive species management by the water industry. *Water Research*, 178, 115771. <https://doi.org/10.1016/j.watres.2020.115771>

Gallardo, B., Errea, M.P., and Aldridge, D.C. (2012). Application of bioclimatic models coupled with network analysis for risk assessment of the killer shrimp, *Dikerogammarus villosus*, in Great Britain. *Biological Invasions*, 14, 1265–1278. <https://doi.org/10.1007/s10530-011-0154-0>

Garner, G., Malcolm, I.A., Sadler, J.P., Hannah, D.M. (2017). The role of riparian vegetation density, channel orientation and water velocity in determining river temperature dynamics. *Journal of Hydrology*, 553, 471- 485. <https://doi.org/10.1016/j.jhydrol.2017.03.024>

Garrett, A., Buckley, P., Brown, S. (2015). Understanding and responding to climate change in the UK seafood industry: Climate change risk adaptation for wild capture seafood. A Seafish report to the UK Government under the Climate Change Adaptation Reporting Power. Retrieved from <https://www.seafish.org/document/?id=ea8b8232-22da-4da5-b063-f2903648c476>

Garry F.K., Bernie D.J., Davie, J.C.S., Pope, E.C.D. (2021). Future climate risk to UK agriculture from compound events. *Climate Risk Management*, 32, 100282.

<https://doi.org/10.1016/j.crm.2021.100282>

Gazzard, R., McMorrow, J., Ayles, J. (2016). Wildfire policy and management in England: an evolving response from Fire and Rescue Services, forestry and cross-sector groups. *Philosophical Transactions of the Royal Society B*, 371(1696), 20150341. <https://doi.org/10.1098/rstb.2015.0341>

GB Non-native species secretariat. (2019). Check, Clean, Dry Campaign. Retrieved from <http://www.nonnativespecies.org/checkcleandry/>

- GBNNS. (2017). *GB non-native species report card 2017*. Retrieved from <http://www.nonnativespecies.org/downloadDocument.cfm?id=1116>
- Genner, M.J., Freer, J.J., Rutterford, L.A. (2017). Biological Responses to Ocean Warming UK Foresight Report: Future of the Sea project. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/639430/Ocean_warming_final.pdf
- Georgeson, L., and Maslin, M. (2017). *Distribution of climate suitability for viticulture in the United Kingdom in 2100* (ECRC Research Report Number 177). Retrieved from <https://www.geog.ucl.ac.uk/people/academic-staff/mark-maslin/files/Research%20Report%20177.pdf>
- Gethmann, J., Probst, C., Conraths, F.J. (2020). Economic Impact of a Bluetongue Serotype 8 Epidemic in Germany. *Frontiers in Veterinary Science* 7, 65. <https://doi.org/10.3389/fvets.2020.00065>
- Giakoumi, S., Katsanevakis, S., Albano, P.G., Azzurro, E., Cardoso, A.C., Cebrian, E. *et al.* (2019). Management priorities for marine invasive species. *Science of the Total Environment*, 688, 976-982. <https://doi.org/10.1016/j.scitotenv.2019.06.282>
- Gillingham, P.K., Bradbury, R.B., Roy, D.B., Anderson, B.J., Baxter, J.M., Bourn, N.A.D. *et al.* (2015). The effectiveness of protected areas to conserve species undertaking geographic range shifts. *Biological Journal of the Linnean Society*, 115(3), 707–717. <https://academic.oup.com/biolinnean/article/115/3/707/2440222>
- Gillings, S., Balmer, D.E., Fuller, R.J. (2015). Directionality of recent bird distribution shifts and climate change in Great Britain. *Global Change Biology*, 21.6, 2155–2168. <https://doi.org/10.1111/gcb.12823>
- Gioria, M., O'Flynn, C., and Osborne, B. (2019). Managing invasions by terrestrial alien plants in Ireland: Challenges and opportunities. *Biology and Environment: Proceedings of the Royal Irish Academy*, 119B(1), 37-61. <https://doi.org/10.3318/bioe.2019.04>
- Glaves, D.J., Crowle, A.J.W., Bruemmer, C., Lenaghan, S.A. (2020). The causes and prevention of wildfire on heathlands and peatlands in England. Natural England Evidence Review NEER014. Retrieved from Peterborough: <http://publications.naturalengland.org.uk/publication/4741162353295360>
- Glenk, K. and Martin-Ortega, J. (2018). The Economics of Peatland Restoration. *Journal of Environmental Economics and Policy*. V7, p1-18. <http://www.tandfonline.com/doi/full/10.1080/21606544.2018.1434562>
- Glover, J. (2019). Landscapes Review. Report to Defra. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/833726/landscapes-review-final-report.pdf
- Goberville, E., Hautekèete, N-C., Kirby, R. R., Piquot, Y., Luczak, C., Beaugrand, G. (2016). Climate change and the ash dieback crisis. *Scientific Reports* 6, 35303. <https://doi.org/10.1038%2Fsrep35303>
- Gormley, K.S., Porter, J.S., Bell, M.C., Hull, A.D., Sanderson, W.G. (2013). Predictive Habitat Modelling as a Tool to Assess the Change in Distribution and Extent of an OSPAR Priority Habitat under an Increased Ocean Temperature Scenario: Consequences for Marine Protected Area Networks and Management. *PLoS ONE*, 8(7), e68263. <https://doi.org/10.1371/journal.pone.0068263>
- GO-Science and Defra. (2014). Animal and Plant Health in the UK: Building our science capability. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/388571/14-1293-animal-plant-health-capability.pdf

- Goulson, D., Nicholls, E., Botías, C., Rotheray, E.L. (2015). Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science*, 347(6229), 1255957. <https://doi.org/10.1126/science.1255957>
- Graham, A.M., Pope, R.J., McQuaid, J.B., Pringle, K.P., Arnold, S.R., Bruno, A.G. *et al.* (2020). Impact of the June 2018 Saddleworth Moor wildfires on air quality in northern England. *Environmental Research Communications*, 2(3), 031001. <https://doi.org/10.1088/2515-7620/ab7b92>
- Grau-Andrés, R., Davies, G., Waldron, M., Scott, S., Marian, E., Gray, A. (2019). Increased fire severity alters initial vegetation regeneration across Calluna-dominated ecosystems. *Journal of Environmental Management*, 231, 1004-1011. <https://doi.org/10.1016/j.jenvman.2018.10.113>
- Graves, A.R., Morris, J., Deeks, L.K., Rickson, R.J., Kibblewhite, M.G.; Harris, J.A.; Farewell, T.S.; Truckle, I. (2015). The total costs of soil degradation in England and Wales. *Ecological Economics*, 119, 399–413. <https://doi.org/10.1016/j.ecolecon.2015.07.026>
- Gray, E., Elliott, J.A., Mackay, E.B., Folkard, A.M.; Keenan, P.O.; Jones, I.D. (2019). Modelling lake cyanobacterial blooms: Disentangling the climate-driven impacts of changing mixed depth and water temperature. *Freshwater Biology*, 64(12), 2141-2155. <https://doi.org/10.1111/fwb.13402>
- Green, A., Chadwick, M.A., Jones, P.J.S. (2018). Variability of UK seagrass sediment carbon: Implications for blue carbon estimates and marine conservation management. *PLoS ONE* 13(9), e0204431. <https://doi.org/10.1371/journal.pone.0204431>
- Green, A.E., Unsworth, R.K.F., Chadwick, M.A., Jones, P.J.S. (2021). Historical Analysis Exposes Catastrophic Seagrass Loss for the United Kingdom. *Frontiers in plant science*, 12, 629962. <https://doi.org/10.3389/fpls.2021.629962>
- Green, E.J. (2017). *Population responses to climate change of two European warbler species*. University of Cambridge, Retrieved from https://idiscover.lib.cam.ac.uk/permalink/f/t9gok8/44CAM_ALMA21552491180003606
- Gregory, S.D.; Bewes, V.E.; Davey, A.J.H.; Roberts, D.E.; Gough, P.; Davidson, I.C. (2020). Environmental conditions modify density-dependent salmonid recruitment: Insights into the 2016 recruitment crash in Wales. *Freshwater Biology*, 65, 2135–2153. <https://doi.org/10.1111/fwb.13609>
- Griffiths, B., Hargreaves, P. Bhogal, A., Stockdale, E. (2018). Soil Biology and Soil Health Partnership Project 2: Selecting methods to measure soil health and soil biology and the development of a soil health scorecard (Final Report No. 91140002-02). Retrieved from <https://projectblue.blob.core.windows.net/media/Default/Programmes/GREATSoils/Soil Biology and Soil Health Partnership Project 2.pdf>
- Grinsted, A., and Hesselbjerg, J. (2021). The transient sensitivity of sea level rise. *Ocean Sci.*, 17, 181–186. <https://doi.org/10.5194/os-17-181-2021>
- Guerra, C.A., Bardgett, R.D., Caon, L., Crowther, T.W., Delgado-Baquerizo, M., Montanarella, L. *et al.* (2021). Tracking, targeting, and conserving soil biodiversity. *Science*, 371, 239-241. <https://doi.org/10.1126/science.abd7926>
- Guerrieri, R., Vanguelova, E., Pitman, R., Benham, S., Perks, M., Morison, J., Mencuccini, M. (2020). Climate overrides atmospheric deposition in affecting spatial and temporal changes in forest water-use efficiency and nitrogen availability across Britain. *Nature Scientific Reports* 10, 12418. <https://doi.org/10.1038/s41598-020-67562-w>
- Gunawardena, K.R., Wells, M.J., Kershaw, T. (2017). Utilising green and bluespace to mitigate urban heat island intensity. *Science Total Environment*, 584 - 585, 1040 - 1055. <https://doi.org/10.1016/j.scitotenv.2017.01.158>

- Gurney, M. (2015). Gains and losses: extinctions and colonisations in Britain since 1900. *Biological Journal of the Linnean Society*, 115(3), 573–585. <https://doi.org/10.1111/bij.12503>
- Haigh, I.D., Nicholls, R.J., Penning-Roswell, E., Sayers, P. (2020). Impacts of climate change on coastal flooding, relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 546–565. Retrieved from http://www.mccip.org.uk/media/2026/23_coastal_flooding_2020.pdf
- Haigh, I.D., Pickering, M.D., Green, J.A.M., Arbic, B. K., Arns, A., Dangendorf, S. *et al.* (2019). The tides they are a-changin': A comprehensive review of past and future nonastronomical changes in tides, their driving mechanisms and future implications. *Reviews of Geophysics*, 57, e2018RG000636. <https://doi.org/10.1029/2018RG000636>
- Hallett, P., Hall, R., Lilly, A., Baggaley, B., Crooks, B., Ball, B. *et al.* (2016). Effect of soil structure and field drainage on water quality and flood risk (Report CRW2014_03). Retrieved from https://www.crew.ac.uk/sites/www.crew.ac.uk/files/publication/CRW2014_03_Soil_Structure_Drainage_Flood_Risk_Main_Report.pdf
- Hannah, D.M., and Garner, G. (2015). River water temperature in the United Kingdom: Changes over the 20th century and possible changes over the 21st century. *Progress in Physical Geography: Earth and Environment*, 39, 68-92. <https://doi.org/10.1177%2F0309133314550669>
- Hansom, J.D., Fitton, J.M., Rennie, A.F. (2017). Dynamic Coast - National Coastal Change Assessment: National Overview (CRW2014/2). Retrieved from <http://www.dynamiccoast.com/files/reports/NCCA%20-%20National%20Overview.pdf>
- Hargreaves, P.R., Baker, K.L., Graceson, A., Bonnett, S., Ball, B.C., Cloy, J.M. (2019). Soil compaction effects on grassland silage yields and soil structure under different levels of compaction over three years. *European Journal of Agronomy*, 109, 125916. <https://doi.org/10.1016/j.eja.2019.125916>
- Harkin, D., Davies, M., Hyslop, E., Fluck, H., Wiggins, M., Merritt, O. *et al.* (2020). Impacts of climate change on cultural heritage. *MCCIP Science Review*, 616 – 641. Retrieved from http://www.mccip.org.uk/media/2029/26_cultural_heritage_2020.pdf
- Harkness, C., Semenov, M.A., Areal, F., Senapati, N., Trnka, M., Balek, J. Bishop, J. (2020). Adverse weather conditions for UK wheat production under climate change. *Agricultural and Forest Meteorology*, 282-283. <https://doi.org/10.1016/j.agrformet.2019.107862>
- Haro-Montegudo, D., Daccache, A., Knox, J. (2018). Exploring the utility of drought indicators to assess climate risks to agricultural productivity in a humid climate. *Hydrology Research*, 49(2), 539-551. <https://doi.org/10.2166/nh.2017.010>
- Harries, T., and Penning-Rowsell, E. (2011). Victim pressure, institutional inertia and climate change adaptation: The case of flood risk. *Global Environmental Change* 21(1), 188-197. <https://doi.org/10.1016/j.gloenvcha.2010.09.002>
- Harrison, P A., Dunford, R.W., Holman, I.P., Rounsevell, M.D.A. (2016). Climate change impact modelling needs to include cross-sectoral interactions. *Nature Climate Change*, 6, 885-890. <https://doi.org/10.1038/nclimate3039>
- Harrison, S. (2020). Plant community diversity will decline more than increase under climatic warming. *Philosophical Transactions of the Royal Society B*, 375(1794). <http://doi.org/10.1098/rstb.2019.0106>
- Harrower, C.A., Rorke, S.L., Roy, H.E. (2019). *England biodiversity indicators. Indicator 20 Pressure from invasive species – technical document*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/829137/20_Invasive_Species_TechBG_2019.pdf

- Harvell, C.D., Altizer, S., Cattadori, I.M., Harrington, L., Weil, E. (2009). Climate change and wildlife diseases: When does the host matter the most? *Ecology*, *90*, 912–920. <https://doi.org/10.1890/08-0616.1>
- Hastings, R.A., Rutterford, L.A., Freer, J.J., Collins, R.A., Simpson, S.D., Genner, M.J. (2020). Climate Change Drives Poleward Increases and Equatorward Declines in Marine Species. *Current Biology*, *30*(8), 1572 - 1577. <https://doi.org/10.1016/j.cub.2020.02.043>
- Hawkins, C., Pocock, M., Papadopoulou, L., Haines, R., Isaac, N. (2019). Evaluation of Biodiversity 2020. CEH and ICF report for Defra. Retrieved from <http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=20409&FromSearch=Y&Publisher=1&SearchText=BE0170&SortString=ProjectCode&SortOrder=Asc&Paging=10>
- Hayhow, D.B., Ausden, M.A., Bradbury, R.B., Burnell, D., Copeland A.I., Crick H.Q.P. (2017). The state of the UK's birds 2017. Retrieved from <https://www.bto.org/our-science/publications/state-uks-birds/state-uks-birds-2017>
- Hayhow, D.B., Eaton, M.A., Stanbury, A.J., Burns, F., Kirby, W.B., Bailey, N. *et al.* (2019). The State of Nature 2019. Retrieved from <https://nbn.org.uk/wp-content/uploads/2019/09/State-of-Nature-2019-UK-full-report.pdf>
- Haynes, T.A. (2016). Scottish saltmarsh survey national report (Commissioned Report No. 786). Retrieved from <https://www.nature.scot/sites/default/files/2017-05/Publication%202016%20-%20SNH%20Commissioned%20Report%20786%20-%20Scottish%20saltmarsh%20survey%20national%20report%20%28A2215730%29.pdf>
- Heal, G., and Rising, J. (2014). Global Benefits of Marine Protected Areas. *NBER Working Paper Series*. <https://doi.org/10.3386/w19982>
- Hemery, G., Petrokofsky, G., Ambrose-Oji, B., Forster, J., Hemery, T., O'Brien, L. (2020). Awareness, action, and aspirations in the forestry sector in responding to environmental change: Report of the British Woodlands Survey 2020. Retrieved from <https://www.sylva.org.uk/downloads/BWS2020-report.pdf>
- Hemming, D., and Macneill, K. (2020). Use of meteorological data in biosecurity. *Emerg. Top. Life Sci.*, ETL20200078. <https://doi.org/10.1042/ETLS20200078>
- Herbert, R.J., Collins, K., Mallinson, J., Hall, A.E., Pegg, J., Ross, K. *et al.* (2017). Epibenthic and mobile species colonisation of a geotextile artificial surf reef on the south coast of England. *PLoS ONE*, *12*(9), e0184100. <https://doi.org/10.1371/journal.pone.0184100>
- Herbert, R.J.H., Humphreys, J., Davies, C.J., Roberts, C., Fletcher, S., Crowe, T.P. (2016). Ecological impacts of non-native Pacific oysters (*Crassostrea gigas*) and management measures for protected areas in Europe. *Biodiversity Conservation* *25*, 2835–2865. <https://doi.org/10.1007/s10531-016-1209-4>
- Hess, T., Knox, J., Holman, I., Sutcliffe, C. (2020). Resilience of primary food production to a changing climate: on-farm responses to water-related risks. *Water*, *12*(8), 2155. <https://doi.org/10.3390/w12082155>
- Hicks Pries C.E., Castanha C., Porras R.C., Torn M.S. (2017). The whole-soil carbon flux in response to warming. *Science* *355* (6332), 1420-1423. <https://doi.org/10.1126/science.aal1319>
- Hiddink, J., Burrows, M.T., Molinos, J.G. (2014). Temperature tracking by North Sea benthic invertebrates in response to climate change. *Global Change Biology*, *21*(1), 117-129. <https://doi.org/10.1111/gcb.12726>
- Hill, D.L., Wall, E. (2017). Weather influences feed intake and feed efficiency in a temperate climate. *Journal of Dairy Science*, *100*, 2240–2257. <https://doi.org/10.3168/jds.2016-11047>
- Hill, M.O., and Preston, C.D. (2015). Disappearance of boreal plants in southern Britain – habitat loss or climate change? *Biological Journal of the Linnean Society* *115*, 598–610. <http://doi.org/10.1111/bij.12500>

- Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J. *et al.* (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences*, *111*, 3292-3297. <https://doi.org/10.1073/pnas.1222469111>
- HM Government. (2013). UK Economics of Climate Resilience. Retrieved from [http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=18016#:~:text=Economics%20of%20Climate%20Resilience%20\(ECR\)%20%2D%20CA0401&text=This%20project%20assesses%20the%20extent,organisations%2C%20or%20individuals%20is%20needed.&text=The%20project%20will%20inform%20the%20National%20Adaptation%20Programme](http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=18016#:~:text=Economics%20of%20Climate%20Resilience%20(ECR)%20%2D%20CA0401&text=This%20project%20assesses%20the%20extent,organisations%2C%20or%20individuals%20is%20needed.&text=The%20project%20will%20inform%20the%20National%20Adaptation%20Programme).
- HM Government. (2018a). UK Biological Security Strategy. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/730213/2018_UK_Biological_Security_Strategy.pdf
- HM Government. (2018b). A Green Future: Our 25 Year Plan to Improve the Environment. Retrieved from <https://www.gov.uk/government/publications/25-year-environment-plan>
- HM Government. (2019). Climate change and vector-borne disease in humans in the UK. *POSTnote*. Retrieved from <https://post.parliament.uk/research-briefings/post-pn-0597/>
- HM Government. (2020). Flood and Coastal Erosion Risk Management: Policy Statement. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/903705/flood-coastal-erosion-policy-statement.pdf
- HM Government. (2019). <https://publications.parliament.uk/pa/cm201919/cmselect/cmenvaud/88/8805.htm>
- Holliday, N.P., Bersch, M., Berx, B., Chafik, L., Cunningham, S., Florindo-López, C. *et al.* (2020). Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic. *Nature Communications*, *11*(1), 1-15. <https://doi.org/10.1038/s41467-020-14474-y>
- Holman, I., Davidson, T. A., Burgess, A., Kelly, A., Eaton, J., Hatton-Ellis, T. (2009). *Understanding the effects of coming environmental change on Bosherton Lakes as a basis for a sustainable conservation management strategy*. CCW Contract Science Report No. 858. 134pp. https://www.researchgate.net/publication/263294183_Understanding_the_effects_of_coming_environmental_change_on_Bosherton_Lakes_as_a_basis_for_a_sustainable_conservation_management_strategy/link/0f31753a7f0450e48e000000/download
- Holt, J., Polton, J., Huthnance, J., Wakelin, S., O’Dea, E., Harle, J. *et al.* (2018). Climate-driven change in the North Atlantic and Arctic Oceans can greatly reduce the circulation of the North Sea. *Geophysical Research Letters*, *45*(21), 11,827–811,836. <https://doi.org/10.1029/2018GL078878>
- Horrill, J.C., Oliver, M.K., and Stubbs Partridge, J. (2019). *Lessons on effectiveness and long-term prevention from broad-scale control of invasive alien species in Scotland’s rivers and lochs* (Occasional Paper SSC no. 62). Retrieved from Gland, Switzerland: http://www.issg.org/pdf/publications/2019_Island_Invasives/Horrill.pdf
- Horton, B.P., Shennan, I., Bradley, S.L., Cahill, N., Kirwan, M., Kopp, R.E., Shaw, T.A. (2018). Predicting marsh vulnerability to sea-level rise using Holocene relative sea-level data. *Nature Communications*, *9*, 1-7. <https://doi.org/10.1038/s41467-018-05080-0>
- Houdijk, J.G.M., Tolkamp, B.J., Rooke, J.A., Hutchings, M.R. (2017). Animal health and greenhouse gas intensity: The paradox of periparturient parasitism. *International Journal for Parasitology*, *47*(10 - 11), 633-641. <https://doi.org/10.1016/j.ijpara.2017.03.006>
- House of Commons Environment, Food and Rural Affairs Committee. (2019). Coastal flooding and erosion, and adaptation to climate change: Interim Report. Retrieved from <https://publications.parliament.uk/pa/cm201919/cmselect/cmenvfru/56/56.pdf>

- House of Commons Environmental Audit Committee. (2019b). House of Commons Environmental Audit Committee Invasive species. First Report of Session 2019. Retrieved from <https://publications.parliament.uk/pa/cm201919/cmselect/cmenvaud/88/88.pdf>
- House of Lords. (2018). *Brexit: plant and animal biosecurity* (21st Report of Session 2017-2019. HL Paper 191). Retrieved from <https://old.parliament.uk/brexit-plant-animal-biosecurity/>
- House of Lords. (2019). <https://www.theyworkforyou.com/lords/?id=2019-01-22a.662.3>
- Howells, R. J., Burthe, S. J., Green, J., Harris, M. P., Newell, M. A., Butler, A., & Daunt, F. (2017). From days to decades: Short- and long-term variation in environmental conditions affect diet composition of a marine top-predator. *Marine Ecology Progress Series*, 583, 227– 242. <https://doi.org/10.3354/meps12343>
- Howells, R. J., Burthe, S. J., Green, J. A., Harris, M. P., Newell, M. A., Butler, A., Wanless, S., & Daunt, F. (2018). Pronounced long-term trends in year-round diet composition of the European shag *Phalacrocorax aristotelis*. *Marine Biology*, 165(12), 1– 15. <https://doi.org/10.1007/s00227-018-3433-9>
- Hristov, J., Toreti, A., Pérez Domínguez, I., Dentener, F., Fellmann, T., Elleby C. *et al.* (2020). *Analysis of climate change impacts on EU agriculture by 2050* (EUR 30078 EN). Retrieved from Publications Office of the European Union, Luxembourg: <https://doi.org/10.2760/121115>
- HR Wallingford. (2020). *Technical Report, Updated projections of future water availability for the third UK Climate Change Risk Assessment* (RT002 R05-00). Retrieved from <https://www.theccc.org.uk/publication/climate-change-risk-assessment-ii-updated-projections-for-water-availability-for-the-uk/>
- Hubble, D.S. (2014). *A review of the scarce and threatened beetles of Great Britain: The leaf beetles and their allies Chrysomelidae, Megalopodidae and Orsodacnidae Species Status No.19* (Natural England Commissioned Report NECR161). Retrieved from <http://publications.naturalengland.org.uk/publication/6548461654638592>
- Hulme, P.E. (2016). Climate change and biological invasions: evidence, expectations, and response options. *Biological Reviews* 92(3), 1297 - 1313. <https://onlinelibrary.wiley.com/doi/full/10.1111/brv.12282>
- Humphreys, M.P., Artioli, Y., Bakker, D.C.E., Hartman, S.E., León, P., Wakelin, S. *et al.* (2020). Air–sea CO₂ exchange and ocean acidification in UK seas and adjacent waters. *MCCIP Science Review 2020*, 54– 75. Retrieved from http://www.mccip.org.uk/media/2006/03_ocean_acidification_2020.pdf
- Huq, N., and Stubbings, A. (2015). How is the role of ecosystem services considered in local level flood management policies: case study in Cumbria, England. *Journal of Environmental Assessment Policy and Management*, 17(4), 1550032. <https://doi.org/10.1142/S1464333215500325>
- Hurst, M.D., Rood, D.H., Ellis, M.A., Anderson, R.S., Dornbusch, U. (2016). Recent acceleration in coastal cliff retreat rates on the south coast of Great Britain. *PNAS*, 113, 13336–13341. <https://doi.org/10.1073/pnas.1613044113>
- ICES Advisory Committee. (2018). *Report of the working group on North Atlantic salmon (WGNAS)* (ICES CM 2018/ACOM:21). Retrieved from http://ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/acom/2018/WGNAS/wgnas_2018.pdf
- ICES Advisory Committee. (2016). *Report of the Working Group on North Atlantic Salmon (WGNAS) 30 March–8 April 651 2016*. Copenhagen. doi:ICES CM 2016/ACOM:10. Retrieved from https://www.ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/acom/2016/WGNAS/wgnas_2016.pdf

- IPBES. (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Retrieved from Bonn, Germany: <https://ipbes.net/global-assessment>
- IPBES (2020). *IPBES Workshop on Biodiversity and Pandemics. Final Report*. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Retrieved from https://ipbes.net/sites/default/files/2020-10/20201028%20IPBES%20Pandemics%20Workshop%20Report%20Plain%20Text%20Final_0.pdf
- IPCC. (2019). Special Report on the Ocean and Cryosphere in a Changing Climate Retrieved from <https://www.ipcc.ch/srocc/>
- IRAG. (2018). *Insecticide resistance status in UK cereal crops*. Retrieved from [https://media.ahdb.org.uk/media/Default/Imported Publication Docs/AHDB Cereals & Oilseeds/Pests/IRAG2 Insecticide resistance status in UK cereal crops.pdf](https://media.ahdb.org.uk/media/Default/Imported%20Publication%20Docs/AHDB%20Cereals%20&%20Oilseeds/Pests/IRAG2%20Insecticide%20resistance%20status%20in%20UK%20cereal%20crops.pdf)
- IUCN. (2016). IUCN Resolution 69 on Defining Nature-based Solutions (WCC-2016-Res-069). IUCN Resolutions, Recommendations and Other Decisions. Retrieved from https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2016_RES_069_EN.pdf
- IUCN. (2018). UK Peatland Strategy 2018-2040. Retrieved from <https://www.iucn-uk-peatlandprogramme.org/uk-strategy>
- IUCN. (2020). IUCN Global Standard for Nature-based Solutions, First edition. Gland, Switzerland. Retrieved from <https://www.iucn.org/theme/nature-based-solutions/resources/iucn-global-standard-nbs>
- Jacobs UK Ltd. (2018). Research to assess the economics of coastal change management in England and to determine potential pathways for a sample of exposed communities (B2334200). Retrieved from <https://www.theccc.org.uk/wp-content/uploads/2018/12/Economics-of-coastal-change-management-in-England-Jacobs.pdf>
- IUCN SSC. (2013). Guidelines for Reintroductions and Other Conservation Translocations. Retrieved from Gland, Switzerland. <https://www.iucn.org/content/guidelines-reintroductions-and-other-conservation-translocations>
- Jackson, F.L., Fryer, R.J., Hannah, D.M., Millar, C.P., Malcolm, I.A. (2018). A Spatio-Temporal Statistical Model of Maximum Daily River Temperatures to Inform the Management of Scotland's Atlantic Salmon Rivers Under Climate Change. *Science Total Environment*. <https://doi.org/10.1016/j.scitotenv.2017.09.010>
- Jackson, M.C., and Grey, J. (2013). Accelerating rates of freshwater invasions in the catchment of the River Thames. *Biological Invasions*, 15(5), 945 - 951. <https://doi.org/10.1007/s10530-012-0343-5>
- Jacquot, M., Nomikou, K., Palmarini, M., Mertens, P. and Biek, R. (2017). Bluetongue virus spread in Europe is a consequence of climatic, landscape and vertebrate host factors as revealed by phylogeographic inference. *Proceedings of the Royal Society B: Biological Sciences*, 284(1864), 20170919. <https://doi.org/10.1098/rspb.2017.0919>
- Jarvie, H.P., Neal, C., Juergens, M.D., Sutton, E.J., Neal, M., Wickham, H.D. *et al.* (2006). Within-river nutrient processing in Chalk streams: The Pang and Lambourn, UK. *Journal of Hydrology*, 330(1 - 2), 101–125. <https://doi.org/10.1016/j.jhydrol.2006.04.014>
- Jaroszweski, D., Wood, R. and Chapman, L. (2021) Infrastructure. In: *The Third UK Climate Change Risk Assessment Technical Report*. [Betts, R.A., Haward, A.B. and Pearson, K.V. (eds)] Prepared for the Climate Change Committee, London <https://www.ukclimaterisk.org/independent-assessment-ccra3/technical-report/>

- Jeffreys, R.M., Robson, L.M., Narayanaswamy, B.E. (2020). Impacts of climate change on deep-sea habitats relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 293–321. <https://doi.org/doi:%2010.14465/2020.arc14.dsh>
- JNCC. (2016). Common standards monitoring guidance for rivers. Retrieved from Peterborough: http://jncc.defra.gov.uk/pdf/CSM_rivers_Sept2016.pdf
- JNCC. (2019). UK Biodiversity Indicators 2019 Fiche. Retrieved from http://jncc.defra.gov.uk/pdf/CSM_rivers_Sept2016.pdf
- JNCC. (2020) Special Protection Areas Overview. <https://jncc.gov.uk/our-work/special-protection-areas-overview/-spa-reviews>.
- JNCC. (2020). Sustainable Fisheries. Retrieved from <https://jncc.gov.uk/our-work/ukbi-b2-sustainable-fisheries/>
- Johnson, C.A., Acreman, M.C., Dunbar, M.J., Feist, S.W., Giacomello, A., Gozlan, R.E. *et al.* (2009). The British river of the future: How climate change and human activity might affect two contrasting river ecosystems in England. *Science of the Total Environment*, 407(17), 4787–4798. <https://doi.org/10.1016/j.scitotenv.2009.05.018>
- Johnson, M.F., and Wilby, R.L. (2015). Seeing the landscape for the trees: Metrics to guide riparian shade management in river catchments. *Water Resources Research* 51, 3754-3769. <https://doi.org/10.1002/2014WR016802>
- Johnston, A., Ausden, M., Dodd, A., Bradbury, R.B., Chamberlian, D.E., Jiguet, F. *et al.* (2013). Observed and predicted effects of climate change on species abundance in protected areas. *Nature Climate Change*, 3, 1055–1061. <https://doi.org/10.1038/nclimate2035>
- Jones, A.E., Turner, J., Caminade, C., Heath, A.E., Wardeh, M., Kluiters, G. *et al.* (2019). Bluetongue risk under future climates. *Nature Climate Change*, 9, 153 - 157. <https://doi.org/10.1038/s41558-018-0376-6>
- Jones, B.A. (2017). Invasive Species Impacts on Human Well-being Using the Life Satisfaction Index. *Ecological Economics*, 134, 250-257. <https://doi.org/10.1016/j.ecolecon.2017.01.002>
- Jones, I., Abrahams, C., Brown, L., Dale, K., Edwards, F., Jeffries, M. *et al.* (2013). The impact of extreme events on freshwater ecosystems. *Ecological Issues*, 12, 67. Retrieved from https://www.researchgate.net/publication/319968451_The_Impact_of_Extreme_Events_on_Fresh_water_Ecosystems
- Jones, L., Gorst, A., Elliott, J., Fitch, A., Illman, H., Evans, C. *et al.* (2020). Climate driven threshold effects in the natural environment. Retrieved from https://www.ukclimaterisk.org/wp-content/uploads/2020/07/Thresholds-in-the-natural-environment_CEH.pdf
- Jones, L.M., Koehler, A-K., Trnka, M., Balek, J., Challinor, A.J., Atkinson, H.J., Urwin, P.E. (2017). Climate change is predicted to alter the current pest status of *Globodera pallida* and *G. rostochiensis* in the United Kingdom. *Global Change Biology*, 23, 4497 - 4507. <https://doi.org/10.1111/gcb.13676>
- Jones, M., Dye, S., Pinnegar, J., Warren, R., Cheung, W. (2015). Using scenarios to project the changing profitability of fisheries under climate change. *Fish and Fisheries*, 16, 603–622. <https://doi.org/10.1111/faf.12081>
- Junk, J., Kouadio, L., Delfosse, P., El Jarroudi, M. (2016). Effects of regional climate change on brown rust disease in winter wheat. *Climatic Change* 135, 439-451. <https://doi.org/10.1007/s10584-015-1587-8>
- Kahiluoto, H., Kaseva, J., Balek, J., Olesen, J.E., Ruiz-Ramos, M., Gobin, A. *et al.* (2019). Decline in climate resilience of European wheat. *PNAS*, 116, 123–128. <https://doi.org/10.1073/pnas.1804387115>
- Kay, A.L. (2015). A review of snow in Britain: The historical picture and future projections. *Prog in Phys Geog*, 40, 676–698. <https://doi.org/10.1177/0309133316650617>

- Keay, C.A. (2020). Rerun SP1104 with UKCP18 data. Capability, Suitability and Climate Programme. Retrieved from https://gov.wales/sites/default/files/publications/2020-12/capacity-suitability-climate-programme-2012-study-rerun_0.pdf
- Keay, C.A., and Hannam, J.A. (2020). The effect of Climate Change on Agricultural Land Classification (ALC) in Wales. Capability, Suitability and Climate Programme, Welsh Government Report 95. Retrieved from <https://gov.wales/sites/default/files/publications/2020-12/agricultural-land-classification-projected-effect-climate-change.pdf>
- Keay, C.A., Jones, R.J., Hannam, J.A., and Barrie, I.A. (2014). The implications of a changing climate on agricultural land classification in England and Wales. *The Journal of Agricultural Science*, 152(1), 23-37. <http://dx.doi.org/10.1017/S0021859612000822>
- Keeley, A.T.H., Beier, P. and Jenness, J.S. (2021). Connectivity metrics for conservation planning and monitoring. *Biological Conservation*, 255, 109008. <https://doi.org/10.1016/j.biocon.2021.109008>.
- Keeling, M.J., Franklin, D.N., Datta, S., Brown, M.A., and Budge, G.E. (2017). Predicting the spread of the Asian hornet (*Vespa velutina*) following its incursion into Great Britain. *Scientific Reports*, 7(1), 1-7. <https://doi.org/10.1038/s41598-017-06212-0>
- Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A. (2018). The superior effect of nature based solutions in land management for enhancing ecosystem services. *Sci Total Environ*, 610-611, 997-1009. <https://doi.org/10.1016/j.scitotenv.2017.08.077>
- Kell, S., Rosenfeld, A, Cunningham, S., Dobbie, S., and Maxted, N. (2018). The benefits of exotic food crops cultivated by small-scale growers in the UK. *Renewable Agriculture and Food Systems*, 33(6), 569-584. <https://doi.org/10.1017/S1742170517000424>
- Keller, T., Sandin, M., Colombi, T., Horn, R., Or, D. (2019). Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil and Tillage Research*, 194, 104293. <https://doi.org/10.1016/j.still.2019.104293>
- Kelly, R., Boston, E., Montgomery, W.I., Reid, N (2016). The role of the seed bank in recovery of temperate heath and blanket bog following wildfires. *Applied Vegetation Science*, 19(4), 620-633. <https://doi.org/10.1111/avsc.12242>
- Kelly, R., Leach, K., Cameron, A., Maggs, C.A., Reid, N. (2014). Combining global climate and regional landscape models to improve prediction of invasion risk. *Diversity Distrib*, 20, 884-894. <https://doi.org/10.1111/ddi.12194>
- Kendon, M., McCarthy, M., Jevrejeva, S., Matthews, A., Sparks, T., Garforth, J. (2020). State of the UK Climate 2019. *International Journal of Climatology*, 40 (S1). 1-69. <https://doi.org/10.1002/joc.6726>
- Kennedy-Asser, A.T., Andrews, O., Mitchell, D.M., Warren, R.F. (2021). Evaluating heat extremes in the UK Climate Projections (UKCP18). *Environmental Research Letters* 16, 014039. <https://doi.org/10.1142/S1464333215500325>
- Kenter, J.O., Bryce, R., Davies, A., Jobstvogt, N., Watson, V., Ranger, S. *et al.* (2013). The value of potential marine protected areas in the UK to divers and sea anglers (UNEP-WCMC). Retrieved from Cambridge, UK: <http://uknea.unep-wcmc.org/LinkClick.aspx?fileticket=Mb8nUAphh%2BY%3D&tabid=82>
- Kernan, M. (2015). Climate change and the impact of invasive species on aquatic ecosystems. *Aquatic Ecosystem Health & Management*, 18(3), 321-333. <https://doi.org/10.1080/14634988.2015.1027636>
- Kiesel, J., Schuerch, M., Christie, E.K., Möller, I., Spencer, T., and Vafeidis, A.T. (2020). Effective design of managed realignment schemes can reduce coastal flood risks. *Estuarine, Coastal and Shelf Science*, 106844. <https://doi.org/10.1016/j.ecss.2020.106844>

- Kipling, R.P., Virkajarvi, P., Breitsameter, L., Curnel, Y., De Swaef, T., Gustavsson, A.-M., et al. (2016). Key challenges and priorities for modelling European grasslands under climate change. *Science of the Total Environment*, 566–567. <https://doi.org/10.1016/j.scitotenv.2016.05.144>
- Knights, A.M. (2014). Modelling the response of the twaite shad (*Alosa fallax*) population in the Afon Tywi SAC to a modified temperature regime. (NRW Evidence Report No: 6). Retrieved from Bangor: <https://cdn.cyfoethnaturiol.cymru/media/684843/report-006-modelling-alosa-fallax-pop-afon-tywi-sac-to-modified-temperature.pdf>
- Knox, J.W., Haro-Montegudo, D., Hess, T.M., Morris, J. (2018). Identifying trade-offs and reconciling competing demands for water: Integrating agriculture into a robust decision-making framework. *Earth's Future*, 6(10), 1457-1470. <https://doi.org/10.1002/2017EF000741>
- Köpsel, V., Walsh, C., Leyshon, C. (2017). Landscape narratives in practice: implications for climate change adaptation. *The Geographical Journal*, 183(2), 175–186. <https://doi.org/10.1111/geoj.12203>
- Kovats, S. and Brisley, R. (2021) Health, communities and the built environment. In: *The Third UK Climate Change Risk Assessment Technical Report* [Betts, R.A., Haward, A.B. and Pearson, K.V. (eds.)]. Prepared for the Climate Change Committee, London <https://www.ukclimaterisk.org/independent-assessment-ccra3/technical-report/>
- Krause-Jensen, D., Lavery, P., Serrano, O., Marbà, N., Masque, P., Duarte, C.M. (2018). Sequestration of macroalgal carbon: the elephant in the Blue Carbon room. *Biology letters*, 14(6), 20180236. <https://doi.org/10.1098/rsbl.2018.0236>
- Kuhlman, T., Reinhard, S., Gaaff, A. (2010). Estimating the costs and benefits of soil conservation in Europe. *Land Use Policy*, 27(1), 22–32. <https://doi.org/10.1016/j.landusepol.2008.08.002>
- Kuklicke, C., and Demeritt, D. (2016). Adaptive and risk-based approaches to climate change and the management of uncertainty and institutional risk: The case of future flooding in England. *Global Environmental Change*, 37, 56-68. <https://doi.org/10.1016/j.gloenvcha.2016.01.007>
- Küpper, F.C., and Kamenos, N.A. (2018). The future of marine biodiversity and marine ecosystem functioning in UK coastal and territorial waters (including UK Overseas Territories)–with an emphasis on marine macrophyte communities. *Botanica Marina*, 61(6), 521-535. <https://doi.org/10.1515/bot-2018-0076>
- Kurylyk, B.L., MacQuarrie, K.T., Linnansaari, T., Cunjak, R.A., and Curry, R.A. (2015). Preserving, augmenting, and creating cold-water thermal refugia in rivers: Concepts derived from research on the Miramichi River, New Brunswick (Canada). *Ecohydrology* 8(6), 1095-1108. <https://doi.org/10.1002/eco.1566>
- Ladd, C.J., Duggan-Edwards, M.F., Bouma, T.J., Pagès, J.F., and Skov, M.W. (2019). Sediment supply explains long-term and large-scale patterns in salt marsh lateral expansion and erosion. *Geophysical Research Letters*, 46(20), 11178-11187. <https://doi.org/10.1029/2019GL083315>
- Laffoley, D., Grimsditch, G. (eds). (2009). The management of natural coastal carbon sinks. Gland, Switzerland: IUCN. <https://www.researchgate.net/publication/252896445> The Management of Natural Coastal Carbon Sinks
- Laizé, C., Acreman, M. and Overton, I. (2017). Projected novel eco-hydrological river types for Europe. *Ecohydrology & Hydrobiology*, 17, 73-83. <https://doi.org/10.1016/j.ecohyd.2016.12.006>
- Lake, P.S. (2011). Drought and aquatic ecosystems: effects and responses. Wiley-Blackwell, UK. ISBN: 978-1-405-18560-8
- Lancaster, L.T., Morrison, G., Fitt, R.N. (2017). Life history trade-offs, the intensity of competition, and coexistence in novel and evolving communities under climate change. *Philosophical Transactions of the Royal Society B*, 372(1712). <http://doi.org/10.1098/rstb.2016.0046>

- Land Use Consultants. (2019). North Norfolk Landscape Character Assessment. Retrieved from <https://www.north-norfolk.gov.uk/media/4720/north-norfolk-landscape-character-assessment-2018-final-draft-spd.pdf>
- Langton, R., Stirling, D.A., Boulcott, P. and Wright, P.J. (2020). Are MPAs effective in removing fishing pressure from benthic habitats and species? *Biological Conservation* 247, 10851. <https://doi.org/10.7489/12270-1>
- Lask, J., Wagner, M., Trindade, L.M., and Lewandowski, I. (2019). Life cycle assessment of ethanol production from miscanthus: A comparison of production pathways at two European sites. *GCB Bioenergy*, 11(1), 269-288. <https://doi.org/10.1111/gcbb.12551>
- Laverty, C., Brenner, D., McIlwaine, C., Lennon, J.J., Dick, J.T.A., Lucy, F.E., Christian, K.A. (2017). Temperature rise and parasitic infection interact to increase the impact of an invasive species. *International Journal for Parasitology*, 47(5), 291-296. <https://doi.org/10.1016/j.ijpara.2016.12.004>
- Lawrence, A., and Marzano, M. (2014). Is the private forest sector adapting to climate change? A study of forest managers in north Wales. *Annals of Forest Science* 71, 291–300. <https://doi.org/10.1007/s13595-013-0326-4>
- Lawrence, A. (2020). Diversifying conifers in productive forests: stakeholders' perspectives. Retrieved from Scotland: <https://www.climateexchange.org.uk/research/projects/diversifying-conifers-in-productive-forests-stakeholders-perspectives/>
- Lawton, J.H., Brotherton, P.N.M., Brown, V.K., Elphick, C., Fitter, A.H., Forshaw, J., Haddow, R.W., Hilborne, S., Leafe, R.N., Mace, G.M., Southgate, M.P., Sutherland, W.J., Tew, T.E., Varley, J., Wynne, G.R. (2010). Making Space for Nature: a review of England's wildlife sites and ecological network. Report to Defra. Retrieved from <https://webarchive.nationalarchives.gov.uk/20130402170324/http://archive.defra.gov.uk/environment/biodiversity/documents/201009space-for-nature.pdf>
- Leach, K., Kelly, R., Cameron, A., Montgomery, W.I, Reid, N. (2015). Expertly validated models and phylogenetically-controlled analysis suggests responses to climate change are related to species traits in the Order Lagomorpha. *PLoS ONE*, 10. <https://doi.org/10.1371/journal.pone.0122267>
- Lecerf, R., Ceglar, A., Lopez-Lozano, R., Van Der Velde, M., Baruth, B. (2019). Assessing the information in crop model and meteorological indicators to forecast crop yield over Europe. *Agricultural Systems*, 168, 191–202. <https://doi.org/10.1016/j.agsy.2018.03.002>
- Lee, M.A., Davis, A.P., Chagunda, M.G.G., Manning, P. (2017). Forage quality declines with rising temperatures, with implications for livestock production and methane emissions. *Biogeosciences*, 14, 1403–1417. <https://doi.org/10.5194/bg-14-1403-2017>
- Legge, O., Johnson, M., Hicks, N., Jickells, T., Diesing, M., Aldridge, J. *et al.* (2020). Carbon on the northwest European shelf: Contemporary budget and future influences. *Frontiers in Marine Science*, 7, 143. <https://doi.org/10.3389/fmars.2020.00143>
- Lehmann, J., Hansel, C.M., Kaiser, C., Kleber, M., Maher, K., Manzoni, S. *et al.* (2020). Persistence of soil organic carbon caused by functional complexity. *Nature Geoscience* 13, 529–534. <https://doi.org/10.1038/s41561-020-0612-3>
- Leigh, C., Aspin, T.W.H., Matthews, T.J., Rolls, R.J., Ledger, M.E. (2019). Drought alters the functional stability of stream invertebrate communities through time. *J Biogeogr*, 46, 1988– 2000. <https://doi.org/10.1111/jbi.13638>
- Lenoir, J., Bertrand, R., Comte, L., Bourgeaud, L., Hattab, T., Murienne, J. Grenouillet, G. (2020). Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution*, 4(8), 1044-1059. <https://doi.org/10.1038/s41559-020-1198-2>

- Leuven, J.R.F.W., Pierik, H.J., van der Vegt, M., Bouma, T.J., Kleinhans, M.G. (2019). Sea-level-rise-induced threats depend on the size of tide-influenced estuaries worldwide. *Nature Climate Change*, 9, 986–992. <https://doi.org/10.1038/s41558-019-0608-4>
- Li, P., Irvine, B., Holden, J., Mu, X. (2017). Spatial variability of fluvial blanket peat erosion rates for the 21st Century modelled using PESERA-PEAT. *Catena*, 150, 302-316. <https://doi.org/10.1016/j.catena.2016.11.025>
- Lilly, A., Baggaley, N.J., Loades, K.W., McKenzie, B.M., and Troldborg, M. (2018). Soil erosion and compaction in Scottish soils: adapting to a changing climate. ClimateXChange Report. Retrieved from <https://www.climatexchange.org.uk/media/3316/soil-erosion-and-compaction-in-scottish-soils-adapting-to-a-changing-climate.pdf>
- Lilly, A., Baggaley, N.J., Edwards, A.C. (2019). Changes in the carbon concentrations and other soil properties of some Scottish agricultural soils: Evidence from a resampling campaign. *Soil Use and Management*, 36(2), 299-307. <https://doi.org/10.1111/sum.12562>
- Lilly, A., Baggaley, N.J. (Cartographer). (2018). Soil erosion risk map of Scotland (partial cover). Retrieved from <https://soils.environment.gov.scot/maps/risk-maps/>
- Lindner, M., Fitzgerald, J.B., Zimmermann, N.E., Reyer, C., van der Maaten, E., Schelhaas, M-J. *et al.* (2014). Climate change and European forests: what do we know, what are the uncertainties, and what are the implications for forest management? *Journal of Environmental Management* 146, 69-83. <https://doi.org/10.1016/j.jenvman.2014.07.030>
- Littleton, E.W., Harper, A.B., Vaughan, N.E., Oliver, R., Duran-Rojas, M.C., Lenton, T.M. (2020). JULES-BE: representation of bioenergy crops and harvesting in the Joint UK Land Environment Simulator vn5.1. *Geoscientific Model Development*, 13, 1123-1136. <https://doi.org/10.5194/gmd-13-1123-2020>
- Liu, W. Fedorov, A.V., Xie, S.P., and Hu, S. (2020). Climate impacts of a weakened Atlantic Meridional Overturning Circulation in a warming climate. *Science advances*, 6(26), eaaz4876. <https://dx.doi.org/10.1126%2Fsciadv.aaz4876>
- Locatelli, B., Pavageau, C., Pramova, E., Di Gregorio, M. (2015). Integrating climate change mitigation and adaptation in agriculture and forestry: opportunities and trade-offs. *WIREs Climate Change*, 6, 585-598. <https://doi.org/10.1002/wcc.357>
- Lowe, J.A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D. *et al.* (2018). UKCP18 Science Overview Report Retrieved from Exeter, UK: <https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf>
- Lu, Q., Whitehead, P.G., Bussi, G., Futter, M.N., Nizzetto, L. (2017). Modelling metaldehyde in catchments: a River Thames case-study. *Environmental Science: Processes & Impacts*, 19(4), 586-595. <https://doi.org/10.1039/C6EM00527F>
- Lucy, F., Davis, E., Anderson, R., Booy, O., Bradley, K., Britton, R. *et al.* (2020). Horizon scan of invasive alien species for the island of Ireland. *Management of Biological Invasions*, 11(2), 155–177. <https://doi.org/10.3391/mbi.2020.11.2.01>
- Luisetti, T., Turner, R.K., Andrews, J.E., Jickells, T.D., Kröger, S., Diesing, M. *et al.* (2019). Quantifying and valuing carbon flows and stores in coastal and shelf ecosystems in the UK. *Ecosystem Services*, 35, 67-76. <https://doi.org/10.1016/j.ecoser.2018.10.013>
- Lunt, P.H., Fyfe, R.M., Tappin, A.D. (2018). Role of recent climate change on carbon sequestration in peatland systems. *Science of the Total Environment*, 667, 348-358. <https://doi.org/10.1016/j.scitotenv.2019.02.239>

- Lynam, C.P., Llope, M., Möllmann, C., Helaouët, P., Bayliss-Brown, G.A., Stenseth, N.C. (2017). Interaction between top-down and bottom-up control in marine food webs. *Proceedings of the National Academy of Sciences*, 114(8), 1952–1957. <https://doi.org/10.1073/pnas.1621037114>
- Maberly, S.C., O'Donnell, R.A., Woolway, R.I., Cutler, M.E.J., Gong, M., Jones, I.D. *et al.* (2020). Global lake thermal regions shift under climate change. *Nature Communications*, 11, 1232 (2020). <https://doi.org/10.1038/s41467-020-15108-z>
- MacDonald, A., Heath, M., Edwards, M., Furness, R., Pinnegar, J.K., Wanless, S. *et al.* (2015). Climate driven trophic cascades affecting seabirds around the British Isles. *Oceanography and Marine Biology - An Annual Review*, 53, 55–79. <https://doi.org/10.1201/b18733-3>
- Macgregor, C.J., Thomas, C.D., Roy, D.B. (2019). Climate-induced phenology shifts linked to range expansions in species with multiple reproductive cycles per year. *Nat Commun* 10, 4455. <https://doi.org/10.1038/s41467-019-12479-w>
- Maclean, I M.D., Hopkins, J.J., Bennie, J., Lawson, C.R., Wilson, R.J. (2015). Microclimates buffer the responses of plant communities to climate change. *Glob Ecol Biogeography*, 24(11), 1340–1350. <https://doi.org/10.1111/geb.12359>
- Macleod, A., Cottier-Cook, E.J., Hughes, D., Allen, C. (2016). Investigating the Impacts of Marine Invasive Non-Native Species. Natural England Commissioned Reports 223. <http://publications.naturalengland.org.uk/publication/5091100843311104>
- Mahaffey, C., Palmer, M., Greenwood, N., Sharples, J. (2020). Impacts of climate change on dissolved oxygen concentration relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 31–53. <https://doi.org/10.14465/2020.arc02.oxy>
- Mair, L. Hill, J.K., Fox, R., Botham, M., Brereton, T., Thomas, C.D. (2014). Abundance changes and habitat availability drive species' responses to climate change. *Nature Climate Change*, 4, 127–131 <https://doi.org/10.1038/nclimate2086>
- Makinen, H., Kaseva, J., Trnka, M., Balek, J., Kersebaum, K.C., Nendel, C. *et al.* (2018). Sensitivity of European wheat to extreme weather. *Field Crops Research*, 222, 209–217. <https://doi.org/10.1016/j.fcr.2017.11.008>
- Malcolm, I.A., Millar, C.P., Millidine, K.J. (2015). Spatio-temporal variability in Scottish smolt emigration times and sizes. *Scottish Marine and Freshwater Science*, 6(2). Retrieved from <https://data.marine.gov.scot/dataset/spatio-temporal-variability-scottish-smolt-emigration-times-and-sizes>
- Mangi, S., Lee, J., Pinnegar, J.K., Law, R.J., Tyllianakis, E., Birchenough, S.N.R. (2018). The economic impacts of ocean acidification on shellfish fisheries and aquaculture in the United Kingdom. *Environ. Sci. Policy*, 86, 95–105. <https://doi.org/10.1016/j.envsci.2018.05.008>
- Mansour, M.M., and Hughes, A.G. (2017). Summary of results for national scale recharge modelling under conditions of predicted climate change (OR/17/026). Retrieved from <http://nora.nerc.ac.uk/id/eprint/521605/1/OR17026.pdf>
- Mansour, M.M., Wang, L., Whiteman, M., and Hughes, A.G. (2018). Estimation of spatially distributed groundwater potential recharge for the United Kingdom. *Quarterly Journal of Engineering Geology and Hydrogeology*, 51(2), 247-263. <https://doi.org/10.1144/qjegh2017-051>
- Maritime and Coastguard Agency. (2021). Ballast Water Management FAQ. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/949792/Ballast_water_Rev_3_01.21.pdf

- Martay, B., Monteith, D.T., Brewer, M.J., Brereton, T., Shortall, C.R., Pearce-Higgins, J.W. (2016). An indicator highlights seasonal variation in the response of Lepidoptera communities to warming. *Ecological Indicators*, 68, 126 - 133. <http://doi.org/10.1016/j.ecolind.2016.01.057>
- Martre, P., Wallach, D., Asseng, S., Ewert, F., Jones, J. W., Rötter, R. P., et al. (2015). Multimodel ensembles of wheat growth: many models are better than one. *Global Change Biology* 21, 911–925. <https://doi.org/10.1111/gcb.12768>
- Mason, S.C., Palmer, G., Fox, R., Fillings, S., Hill, J.K., Thomas, C.D., Oliver, T.H. (2015). Geographical range margins of many taxonomic groups continue to shift polewards. *Biological Journal of the Linnean Society*, 115, 586 - 597. <https://doi.org/10.1111/bij.12574>
- Masselink, G., Russell, P., Rennie, A., Brooks, S., Spencer, T. (2020). Impacts of climate change on coastal geomorphology and coastal erosion relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 158–189. <https://doi.org/10.14465/2020.arc08.cgm>
- Massimino, D., Beale, C.M., Suggitt, A.J., Crick H.Q.P., Macgregor, N.A., Carroll, M.J. et al. (2020). Can microclimate offer refuge to an upland bird species under climate change? *Landscape Ecology*, 35, 1907–1922. <https://doi.org/10.1007/s10980-020-01069-7>
- Massimino, D., Johnston, A., Pearce-Higgins, J. (2015). The geographical range of British birds expands during 15 years of warming. *Bird Study*, 62, 523–534. <https://doi.org/10.1080/00063657.2015.1089835>
- Massimino, D., Johnston, A., Gillings, S., Jiguet, F., Pearce-Higgins, J. (2017). Projected reductions in climatic suitability for vulnerable British birds. *Climatic Change*, 145, 117–130. <https://link.springer.com/article/10.1007/s10584-017-2081-2>
- Mathiesen, S.S., Thyrring, J., Hemmer-Hansen, J., Berge, J., Sukhotin, A., Leopold, P. et al. (2017). Genetic diversity and connectivity within *Mytilus* spp. in the subarctic and Arctic. *Evolutionary Applications*, 10(1), 39-55. <https://doi.org/10.1111%2Feva.12415>
- McCarthy, G.D., Jackson, L.C., Cunningham, S.A., Holliday, N.P., Smeed, D.A., Stevens, D.P. (2020). Effects of climate change on the Atlantic Heat Conveyor relevant to the UK. *MCCIP Science Review*, 190–207. <https://doi.org/10.14465/2020.arc09.ahc>
- MCCIP. (2020). *Marine Climate Change Impacts: Report Card 2020*. Retrieved from <http://www.mccip.org.uk/impacts-report-cards/full-report-cards/2020/>
- McCracken, A.R., Douglas, G.C., Ryan, C., Destefanis, M., Cooke, L.R. (2017). *Ash dieback on the island of Ireland*. Retrieved from Uppsala, Sweden: <http://hdl.handle.net/11019/1224>
- McDermott Long, O., Warren, R., Price, J., Brereton, T.M., Botham, M.S., Franco, A.M. (2017). Sensitivity of UK butterflies to local climatic extremes: which life stages are most at risk? *Journal of Animal Ecology*, 86(1), 108-116. <https://doi.org/10.1111/1365-2656.12594>
- McKibbin, D. (2016). Legislative and Policy Response to the Risk of Coastal Erosion and Flooding in the UK and Ireland (NIAR 274-16). Retrieved from <http://www.niassembly.gov.uk/globalassets/documents/raise/publications/2016-2021/2016/infrastructure/4316.pdf>
- McQueen, K., and Marshall, C.T. (2017). Shifts in spawning phenology of cod linked to rising sea temperatures. *ICES Journal of Marine Science*, 74(6), 1561–1573. <https://doi.org/10.1093/icesjms/fsx025>
- McVittie, A., Cole, L., and Wreford, A. (2017). Assessing Adaptation Knowledge in Europe: Ecosystem-Based Adaptation. Report to DG Climate by Ecofys. Retrieved from https://ec.europa.eu/clima/sites/clima/files/adaptation/what/docs/ecosystem_based_adaptation_en.pdf

- Mellin, C., Lurgi, M., Matthews, S., MacNeil, M.A., Caley, M.J., Bax, N. *et al.* (2016). Forecasting marine invasions under climate change: Biotic interactions and demographic processes matter. *Biological Conservation*, 204, 459-467. <https://doi.org/10.1016/j.biocon.2016.11.008>
- Méndez, V., Gill, J. A., Alves, J. A., Burton, N. H. K., & Davies, R. G. (2018). Consequences of population change for local abundance and site occupancy of wintering waterbirds. *Diversity and Distributions*, 24(1), 24–35. <https://doi.org/10.1111/ddi.12653>
- Metelmann, S., Caminade, C., Jones, A.E., Medlock, J.M., Baylis, M., and Morse, A.P. (2019). The UK's suitability for *Aedes albopictus* in current and future climates. *Journal of the Royal Society Interface*, 16, 20180761. <http://doi.org/10.1098/rsif.2018.0761>
- Meucci, A., Young, I.R., Hemer, M., Kirezci, E., Ranasinghe, R. (2020). Projected 21st century changes in extreme wind-wave events. *Science advances*, 6(24), eaaz7295. <https://doi.org/10.1126/sciadv.aaz7295>
- Mieszowska, N., Sugden, H., Firth, L.B., Hawkins, S.J. (2014). The Role of Sustained Observations in Tracking Impacts of Environmental Change on Marine Biodiversity and Ecosystems. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 372(2025). <https://doi.org/10.1098/rsta.2013.0339>
- Miilar, C., Malcolm, I.A., Kantola, K., Hannah, D.M., Fryer, R.J. (2012). The influence of forest harvesting on stream temperatures. <https://doi.org/10.7558/bhs.2012.ns37>
- Mikkelsen, T., Alexandersen, S., Astrup, P., Champion, H.J., Donaldson, A.I., Dunkerley, F.N.; *et al.* (2003). Investigation of airborne foot-and-mouth disease virus transmission during low-wind conditions in the early phase of the UK 2001 epidemic. *Atmospheric Chemistry and Physics Discussions, European Geosciences Union*, 3(1), 677-703. Retrieved from <https://hal.archives-ouvertes.fr/hal-00303825/document>
- Miles, R., and Richardson, N. (2018). Sustainable Shores (Technical Report). Retrieved from <https://www.rspb.org.uk/globalassets/downloads/projects/sustainable-shores-project---technical-report.pdf>
- Millane, M. and Caffrey, J. (2014). Risk Assessment of *Hydrocotyle ranunculoides*. Retrieved from <https://invasivespeciesireland.com/wp-content/uploads/2017/08/Hydrocotyle-ranunculoides-Floating-Pennywort1.pdf>
- Miller, R.N.G., Alves, G.S.C., and Van Sluys, M-A. (2017). Plant immunity: unravelling the complexity of plant responses to biotic stresses. *Annals of Botany*, 119, 681-687. <https://doi.org/10.1093/aob/mcw284>
- Milligan, J., O’Riordan, T., Nicholson-Cole, S., Watkinson, A.R. (2009). Nature conservation for future sustainable shorelines: Lessons from seeking to involve the public. *Land Use Policy* 26(2), 203-213 <https://doi.org/10.1016/j.landusepol.2008.01.004>
- Minchin, D., Caffrey, J.M., Haberlin, D., Germaine, D., Walsh, C., Boelens, R., and Doyle, T.K. (2016). First observations of the freshwater jellyfish *Craspedacusta sowerbii* Lankester, 1880 in Ireland coincides with unusually high water temperatures. *BioInvasions Records*, 5(2), 67-74. <https://doi.org/10.3391/bir.2016.5.2.02>
- Mirra, I.M., Oliveira, T.M., Barros, A.M.G., Fernandes, P.M. (2017). Fuel dynamics following fire hazard reduction treatments in blue gum (*Eucalyptus globulus*) plantations in Portugal. *Forest Ecology and Management*, 398, 185-195. <https://doi.org/10.1016/j.foreco.2017.05.016>
- Mitchell, I., Daunt, F., Frederiksen, M., Wade, K. (2020). Impacts of climate change on seabirds, relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 382–399. Retrieved from http://www.mccip.org.uk/media/2020/17_seabirds_2020.pdf

- Mitchell, P.L., and Sheehy, J.E. (2018). Potential yield of wheat in the United Kingdom: How to reach 20 t ha⁻¹. *Field Crops Research*, 224, 115–125. <https://doi.org/10.1016/j.fcr.2018.05.008>
- Mitchell, R.J., Bellamy, P.E., Ellis, C.J., Hewison, R.L., Hodgetts, N.G., Iason, G.R. *et al.* (2019). Collapsing foundations: The ecology of the British oak, implications of its decline and mitigation options. *Biological Conservation*, 233, 316-327. <https://doi.org/10.1016/j.biocon.2019.03.040>
- MMO. (2019). Identifying sites suitable for marine habitat restoration or creation. A report produced for the Marine Management Organisation by ABPmer and AER (Project No: 1135). Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/798829/20190430_MMO1135_Identifying_sites_for_habitat_creation_datalayers_Report_a.pdf
- MMO (2021). Marine Pioneer Programme (2017 – 2020): Testing delivery of the 25 Year Environment Plan: Summary and Recommendations. https://zenodo.org/communities/marine_pioneer_sharing/?page=1&size=20
- Moffat, A.J., Gazzard, R. (2019). Wildfire adaptation and contingency planning in South East England – implementation of current legislation and policy. *Quarterly Journal of Forestry*, 113(3), 160-165. https://www.researchgate.net/publication/334615359_Wildfire_Adaptation_and_Contingency_Planning_in_South_East_England_-_Implementation_of_current_legislation_and_policy
- Moffat, C., Baxter, J., Berx, B., Bosley, K., Boulcott, P., Cox, M. *et al.* (Eds.). (2020). Scotland's Marine Assessment 2020. Retrieved from <http://www.marine.gov.scot/sma/>
- Molenveld, A., and van Buuren, A. (2019). Flood risk and resilience in the Netherlands: In search of an adaptive governance approach. *Water*, 11(12), 2563. <https://doi.org/10.3390/w11122563>
- Monaco, C.J., and Helmuth, B. (2011). Tipping points, thresholds and the keystone role of physiology in marine climate change research. *Advances in Marine Biology*, 60, 123-160. <https://doi.org/10.1016/b978-0-12-385529-9.00003-2>
- Montero-Serra, I., Edwards, M., and Genner, M.J. (2015). Warming Shelf Seas Drive the Subtropicalization of European Pelagic Fish Communities. *Global Change Biology*, 21(1), 144–153. <https://doi.org/10.1111/gcb.12747>
- Moore, P.J. and Smale, D.A. (2020). Impacts of climate change on shallow and shelf subtidal habitats relevant to the coastal and marine environment around the UK. *MCCIP Science Review*, 272–292. Retrieved from http://www.mccip.org.uk/media/2016/13_shallow_shelf_habitats_2020.pdf
- Morecroft, M.D., Crick, H.Q.P., Duffield, S.J. and Macgregor, N.A. (2012). Resilience to climate change: translating principles into practice. *Journal of Applied Ecology*, 49, 547–551. <https://doi.org/10.1111/j.1365-2664.2012.02136.x>
- Moran, D., Wreford, A., Evans, A., Fox, N., Glenk, K., Hutchings, M., McCracken, D., McVittie, A., Mitchell, M., Moxey, A., Topp, K., and Wall, E. (2013). Assessing the preparedness of England's natural resources for a changing climate: Assessing the type and level of adaptation action required to address climate risks in the 'vulnerability hotspots'. Supporting research for the UK Climate Change Committee (CCC). Available at <https://www.theccc.org.uk/publication/assessing-preparedness-englands-natural-resources-changing-climate-assessing-type-level-adaptation-action-required-address-climate-risks-vulnerabil/>
- Morecroft, M.D., Duffield, S.J., Harley, M., Pearce-Higgins, J.W., Stevens, N., Watts, O., and Whitaker, J. (2019). Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science*, 366, eaaw9256. <https://doi.org/10.1126/science.aaw9256>
- Morley, N., and Lewis, J. (2020). Influence of an extreme climatic event on bilateral asymmetry and occurrence of eye flukes in perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*) from a lake in

- southeast England. *Journal of Helminthology*, 94(57), 1 - 7.
<https://doi.org/10.1017/S0022149X19000506>
- Morley, N.J., and Lewis, J.W. (2014). Extreme climatic events and host–pathogen interactions: The impact of the 1976 drought in the UK. *Ecological Complexity*, 17, 1 - 19.
<https://doi.org/10.1016/j.ecocom.2013.12.001>
- Morris, R.K.A., Harley, M., Cottle, R., Banks, B., Doody, J.P., Brown, A.E., Weston, A., Hart, R., Prince, S. (2016). Review of the Effectiveness of Natura 2000 Sites Compensation Measures in England. Final Report to Defra. <http://www.humburnature.co.uk/admin/resources/13694wc1076finalreport-1.pdf>
- Mortazavi-Naeini, M., Bussi, G., Elliot, J.A., Hall, J.W., Whitehead, P.G. (2019). Assessment of Risks to Public Water Supply From Low Flows and Harmful Water Quality in a Changing Climate. *Advanced Earth and Space Science*, 55(12), 10386-10404. <https://doi.org/10.1029/2018WR022865>
- Moss, B. (2014). Fresh waters, climate change and UK nature conservation. *Freshwater Reviews*, 7, 25 – 75.
<https://doi.org/10.1608/FRJ-7.1.789>
- Motley, G.S. and Bosanquet, S.D.S. (2017). A bryophyte assessment of Coedydd Nedd a Mellte SAC and associated SSSIs, 2006 to 2017 (NRW Evidence Report No: 211). Retrieved from <https://cdn.cyfoethnaturiol.cymru/media/685150/nrw-evidence-report-no-211-a-bryophyte-assessment-of-coedydd-nedd-a-mellte-sac-and-associated-sssis.pdf>
- Moxey, A. and Moran, D. (2014) UK Peatland Restoration: some Economic Arithmetic. *Science of the Total Environment*, 484, p114-120. <https://doi.org/10.1016/j.scitotenv.2014.03.033>
- MSC. (2020). *MSC UK and Ireland Market Report 2020*. Retrieved from https://www.msc.org/docs/default-source/uk-files/marketreport_2020_interactive.pdf
- MSN news. (2020). <https://www.msn.com/en-gb/news/uknews/endangered-species-of-seahorse-returns-to-former-stronghold-due-to-lockdown/ar-BB14URMj?ocid=ientp>
- Muchan, K. (2020). Warming trend revealed in eight decades of Cumbrian lake temperature records. Retrieved from <https://www.ceh.ac.uk/news-and-media/blogs/lakes-hot-water-warming-trend-revealed-eight-decades-cumbrian-lake-temperature>
- Murchie, A.K., and Gordon, A.W. (2013). The impact of the 'New Zealand flatworm', *Arthurdendyus triangulatus*, on earthwork populations in the field. *Biological Invasions*, 15, 569–586. <https://doi.org/10.1007/s10530-012-0309-7>
- Murdy, J., Orford, J.D., Bell, J. (2015). Maintaining legacy data: saving Belfast Harbour (UK) tide-gauge data (1902-2010). *Geo research letters*, 6, 65-73. <https://doi.org/10.1016/j.grj.2015.02.002>
- Murphy, J., Sexton, D., Jenkins, G., Boorman, P., Booth, B., Brown, K. *et al.* (2009) UK Climate Projections science report: Climate change projections, Met Office Hadley Centre
http://cedadocs.ceda.ac.uk/1320/1/climate_projections_full_report.pdf
- Murphy, J.M., Harris, G.R., Sexton, D.M.H., Kendon, E.J., Bett, P.E., Brown, S.J. *et al.* (2018). UKCP18 Land Projections: Science Report Retrieved from <https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Land-report.pdf>
- Narayan, S.; Beck, M.W., Reguero, B.G., Losada, I.J., van Wesenbeeck, B., Pontee, N., *et al.* (2016). The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. *PLoS ONE* 11(5): e0154735. <https://doi.org/10.1371/journal.pone.0154735>
- National Biodiversity Data Centre. (2015). All-Ireland Pollinator Plan 2015-2020. Retrieved from <https://www.biodiversityireland.ie/wordpress/wp-content/uploads/All-Ireland%20Pollinator%20Plan%202015-2020.pdf>

- National Infrastructure Commission. (2021). *Natural Capital and Environmental Net-Gain*. Retrieved from <https://nic.org.uk/app/uploads/Updated-Natural-Capital-Paper-Web-Version-Feb-2021-1.pdf>
- National Species Reintroduction Forum. (2014). The Scottish Code for Conservation Translocations. Retrieved from Inverness: <https://www.nature.scot/scottish-code-conservation-translocations>
- Natural Capital Committee (2020) Advice on using nature based interventions to reach net zero greenhouse gas emissions by 2050. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/879797/ncc-nature-based-interventions.pdf
- Natural England. (2014). An approach to Landscape Character Assessment. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/691184/landscape-character-assessment.pdf
- Natural England. (2017). Long Term Monitoring Network: monitoring soils 2011 to 2016. Access to Evidence Information Note EIN024. Retrieved from <http://publications.naturalengland.org.uk/publication/6457572973871104>
- Natural England. (2019). An approach to landscape sensitivity assessment – to inform spatial planning and land management. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/817928/landscape-sensitivity-assessment-2019.pdf
- Natural England and RSPB. (2020). *Climate Change Adaptation Manual - Evidence to support nature conservation in a changing climate*. Retrieved from York, UK: <http://publications.naturalengland.org.uk/publication/5629923804839936>
- Natural Resources Wales. (2016). The State of Natural Resources report 2016. Retrieved from <https://naturalresources.wales/evidence-and-data/research-and-reports/the-state-of-natural-resources-report-assessment-of-the-sustainable-management-of-natural-resources/?lang=en>
- Natural Resources Wales. (2017). Making woodlands more resilient. Retrieved from <https://naturalresources.wales/guidance-and-advice/environmental-topics/woodland-management/planning-for-the-future/making-woodlands-more-resilient/?lang=en>
- Natural Resources Wales. (2020a). National Peatland Action Programme, 2020-2025. Retrieved from <https://cdn.cyfoethnaturiol.cymru/media/692545/national-peatlands-action-programme.pdf>
- Natural Resource Wales. (2020b). The Second State of Natural Resources Report: SoNaRR2020 Register freshwater key pressures and opportunities. Retrieved from <https://cdn.cyfoethnaturiol.cymru/media/692814/sonarr2020-register-freshwater-key-pressures-and-opportunities.pdf>
- NatureScot (2017). Pollinator Strategy for Scotland 2017-2027. <https://www.nature.scot/pollinator-strategy-scotland-2017-2027>
- NatureScot. (2020). Planning ahead for coastal change guidance. Retrieved from <https://www.nature.scot/guidance-planning-ahead-coastal-change>
- NatureScot (2021). Large-scale features and Marine Protected Areas. Retrieved from: <https://www.nature.scot/landscapes-and-habitats/habitat-types/coast-and-seas/large-scale-features-and-marine-protected-areas>
- Neethling, E., Petitjean, T., Quénot, H., Barbeau, G. (2016). Assessing local climate vulnerability and winegrowers' adaptive processes in the context of climate change. *Mitigation and Adaptation Strategies for Global Change* 22, 777-803. <https://doi.org/10.1007/s11027-015-9698-0>

- Neilson, R., Lilly, A., Aitkenhead, M., Artz, R., Baggaley, N., Giles, M. *et al.* (2020). Measuring the vulnerability of Scottish soils to a changing climate. *ClimateXChange Scotland*. <http://doi.org/10.7488/era/546>
- Nesbitt, A., Dorling, S., Lovett, A. (2018). A suitability model for viticulture in England and Wales: opportunities for investment, sector growth and increased climate resilience. *Journal of Land Use Science*, 13, 414-438. <https://doi.org/10.1080/1747423X.2018.1537312>
- Nesbitt, A., Kemp, B., Lovett, A., Dorling, S. (2016). Impact of recent climate change and weather variability on the viability of UK viticulture – combining weather and climate records with producers' perspectives. *Australian Journal of Grape and Wine Research* 22(2), 324–335. <https://doi.org/10.1111/ajgw.12215>
- Newbery, F., Qi, A., Fitt, B.D. (2016). Modelling impacts of climate change on arable crop diseases: progress, challenges and applications. *Current Opinion in Plant Biology*, 32, 101-109. <https://doi.org/10.1016/j.pbi.2016.07.002>
- Newson, S.E. Moran, N.J., Musgrove, A.J., Pearce-Higgins, J.W., Gillings, S., Atkinson, P.W. *et al.* (2016). Long-term changes in the migration phenology of UK breeding birds detected by large-scale citizen science recording schemes. *Ibis*, 158, 481-495. <https://doi.org/10.1111/ibi.12367>
- Newton, A.C., Guy, D.C., Hackett, C.A. (2019). Grain and straw yield interactions in barley cultivar mixtures. *The Journal of Agricultural Science*, 157(2), 117 - 128. <https://doi.org/10.1017/S0021859619000364>
- Ni, W., Wang, Y., Symonds, A.M., Collins, M.B. (2014). Intertidal flat development in response to controlled embankment retreat: Freiston Shore, The Wash, UK. *Marine Geology*, 355, 260-273. <http://dx.doi.org/10.1016/j.margeo.2014.06.001>
- Nolan, R.H., Drew, D.M., O'Grady, A.P., Pinkard, E.A., Paul, K., Roxburgh, S.H. *et al.* (2018). Safeguarding reforestation efforts against changes in climate and disturbance regimes *Forest Ecology and Management*, 424, 458-467. <https://doi.org/10.1016/j.foreco.2018.05.025>
- Northern Ireland Environment Agency and National Parks and Wildlife Services. <https://invasivespeciesireland.com>
- O'Hanlon, R., Ryan, C., Choiseul, J., Murchie, A.K., Williams, C. (2020). Catalogue of Pests and Pathogens of Trees on the Island of Ireland. *Preprints 2020*, 2020050168. <https://doi.org/10.20944/preprints202005.0168.v1>
- O'Hanlon, R., Wilson J., Cox, D. (2019). Investigations into the declining health of alder (*Alnus glutinosa*) along the river Lagan in Belfast, including the first report of *Phytophthora lacustris* causing disease of *Alnus* in Northern Ireland. <https://doi.org/10.1101/2019.12.13.875229>
- O'Reilly, C.M., Sharma, S., Gray, D.K., Hampton, S.E., Read, J.S., Rowley, R.J. *et al.* (2015). Rapid and highly variable warming of lake surface waters around the globe. 42(24), 10, 773–710,781. <https://doi.org/10.1002/2015GL066235>
- Oaten, J., Brooks, A., Frost, N. (2018). *Coastal Squeeze Evidence and Monitoring Requirement Review* (NRW Report No: 307). Retrieved from Cardiff: <https://cdn.naturalresources.wales/media/689061/nrw-evidence-report-no-307-coastal-squeeze-evidence-and-monitoring-requirement-review.pdf>
- Ockenden, M.C., Hollaway, M.J., Beven, K.J., Collins, A.L., Evans, R., Falloon, P.D. *et al.* (2017). Major agricultural changes required to mitigate phosphorus losses under climate change. *Nature Communications*, 8. <https://doi.org/10.1038/s41467-017-00232-0>
- OECD. (2020). Biodiversity and the economic response to COVID-19: Ensuring a green and resilient recovery. OECD Policy Responses to Coronavirus (COVID-19). Retrieved from <http://www.oecd.org/coronavirus/policy-responses/biodiversity-and-the-economic-response-to-covid-19-ensuring-a-green-and-resilient-recovery-d98b5a09/>

- Office for National Statistics. (2016). Scoping UK coastal margin ecosystem accounts. Retrieved from <https://cy.ons.gov.uk/economy/environmentalaccounts/methodologies/scopingukcoastalmarginecosystemaccounts>
- Office for National Statistics. (2017). *UK natural capital: ecosystem accounts for freshwater, farmland and woodland*. Retrieved from <https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapital/landandhabitatecosystemaccounts#ecosystem-accounts-for-freshwater>
- Office for National Statistics (2018). UK natural capital: ecosystem accounts for urban areas. <https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapital/ecosystemaccountsforurbanareas>
- Office for National Statistics (2019). UK natural capital: peatlands. <https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapitalforpeatlands/naturalcapitalaccounts>
- Ohlberger, J., Thackeray, S.J., Winfield, I.J., Maberly, S.C., Vøllestad, L.A. (2014). When phenology matters: age–size truncation alters population response to trophic mismatch. *Proceedings of the Royal Society B*, 281(1793). <https://doi.org/10.1098/rspb.2014.0938>
- Oliver, T.H., Gillings, S., Pearce-Higgins, J.W., Brereton, T., Crick, H.Q.P., Duffield, S.J. *et al.* (2017). Large extents of intensive land use limit community reorganization during climate warming. *Global Change Biology*, 23(6), 2272-2283. <https://doi.org/10.1111/gcb.13587>
- Oliver, T.H., Marshall, H.H., Morecroft, M.D., Brereton, T., Prudhomme, C., and Huntingford, C. (2015). Interacting effects of climate change and habitat fragmentation on drought-sensitive butterflies. *Nature Climate Change*, 5(10), 941-945. <https://doi.org/10.1038/nclimate2746>
- Olmos, M., Payne, M.R., Nevoux, M., Prévost, E., Chaput, G., Du Pontavice, H., *et al.* (2019). Spatial synchrony in the response of a long range migratory species (*Salmo salar*) to climate change in the North Atlantic Ocean temperatures. *Global Change Biology*, 26(3), 1319-1337. <https://doi.org/10.1111/gcb.14913>
- Oppedal, F., Dempster, T., Stien, L.H. (2011). Environmental drivers of Atlantic salmon behaviour in sea-cages: a review. *Aquaculture*, 311(1-4), 1-18. <https://doi.org/10.1016/j.aquaculture.2010.11.020>
- Oreska, M., and Aldridge, D. (2011). Estimating the financial costs of freshwater invasive species in Great Britain: a standardized approach to invasive species costing. *Biological Invasions*, 13(2), 305 - 319. <https://doi.org/10.1007/s10530-010-9807-7>
- Orford, J.D., Murdy, J. (2015). Presence and possible cause of periodicities in 20th-century extreme coastal surge: Belfast Harbour, Northern Ireland. *Global and Planetary Change*, 133, 254-262. <https://doi.org/10.1016/j.gloplacha.2015.09.002>
- Orr, H.G., Simpson, G.L., des Clers, S., Watts, G., Hughes, M., Hannaford, J. *et al.* (2015). Detecting changing river temperatures in England and Wales. *Hydrological Processes*, 29, 752– 766. <https://doi.org/10.1002/hyp.10181>
- Ortega, A., Geraldi, N.R., Alam, I., Kamau, A.A., Acinas, S.G., Logares, R. *et al.* (2019). Important contribution of macroalgae to oceanic carbon sequestration. *Nature Geoscience*, 12(9), 748-754. <https://doi.org/10.1038/s41561-019-0421-8>
- OSPAR. (2017). Changes in Phytoplankton and Zooplankton Communities. Retrieved from <https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/biodiversity-status/habitats/changes-phytoplankton-and-zooplankton-communities/>
- Otero, J., L'Abée-Lund, J.H., Castro-Santos, T., Leonardsson, K., Storvik, G.O., Jonsson, B. *et al.* (2014). Basin-scale phenology and effects of climate variability on global timing of initial seaward migration of

- Atlantic salmon (*Salmo salar*) temperatures. *Global Change Biology*, 20(1), 61-75.
<https://doi.org/10.1111/gcb.12363>
- Outhwaite, C.L., Gregory, R.D.; Chandler, R.E.; Collen, B.; Isaac, N.J.B. (2020). Complex long-term biodiversity change among invertebrates, bryophytes and lichens. *Nature Ecology Evolution*, 4, 384–392
<https://doi.org/10.1038/s41559-020-1111-z>
- Pakeman, R., Gimona, A., Glendell, M., Yeluripati, J., Addy, S., van Hulst, F. *et al.* (2018). Climate Change, Natural Capital and Adaptation in Scotland’s Marginal Lands. Retrieved from
<https://www.climatechange.org.uk/research/projects/climate-change-natural-capital-and-adaptation-in-scotland-s-marginal-lands>
- Pakeman, R.J., Alexander, J., Beaton, J., Brooker, R., Cummins, R., Eastwood, A. *et al.* (2015). Species composition of coastal dune vegetation in Scotland has proved resistant to climate change over a third of a century. *Global Change Biology*, 21, 3738-3747. <https://doi.org/10.1111/gcb.12999>
- Palmer, G., Platts, P.J., Brereton, T., Chapman, J.W., Dytham, C., Fox, R. *et al.* (2017). Climate change, climatic variation and extreme biological responses. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 372(1723), 20160144. <https://doi.org/10.1098/rstb.2016.0144>
- Panagos, P., Borrelli, P., Robinson, D. (2015). Tackling soil loss across Europe. *Nature*, 526, 195.
<https://doi.org/10.1038/526195d>
- Parliamentary Office of Science and Technology. (2019). POST note 604: Climate Change and Fisheries. Retrieved from <https://post.parliament.uk/research-briefings/post-pn-0604/>
- Parliamentary Office of Science and Technology. (2017). Reform of Freshwater Abstraction. Retrieved from <https://post.parliament.uk/research-briefings/post-pn-0546/>
- Parmesan, C., and Hanley, M.E. (2015). Plants and climate change: complexities and surprises. *Annals of Botany*, 16, 849–864. <https://doi.org/10.1093/aob/mcv169>
- Parsons, D.J., Rey, D., Tanguy, M., Holman, I.P. (2019). Regional variations in the link between drought indices and reported agricultural impacts of drought. *Agricultural Systems*, 173, 119–129.
<https://doi.org/10.1016/j.agsy.2019.02.015>
- Parsons, A.J., Rowarth, J.S., Rasmussen, S. (2011). High-sugar grasses. CAB Reviews: Perspectives in Agriculture, Veterinary Science. *Nutrition and Natural Resources* 6 (46),1-12.
<https://www.cabdirect.org/cabdirect/abstract/20113380215>
- Pavón-Jordán, D., Abdou, W., Azafzaf, H., Balaž, M., Bino, T., Borg, J.J. *et al.* (2020). Positive impacts of important bird and biodiversity areas on wintering waterbirds under changing temperatures throughout Europe and North Africa. *Biological Conservation*, 246,108549.
<https://www.sciencedirect.com/science/article/pii/S000632071931170X>
- Pavón-Jordán, D., Clausen, P., Dagys, M., Devos, K., Encarnação, V., Fox, A.D. *et al.* (2019). Habitat and species mediated short and long-term distributional changes in waterbird abundance linked to variation in European winter weather. *Diversity and Distributions*, 25(2), 225-239.
<https://doi.org/10.1111/ddi.12855>
- Pavón-Jordán, D., Fox, A.D., Clausen, P., Dagys, M., Deceuninck, B., Devos, K. *et al.* (2015). Climate-driven changes in winter abundance of a migratory waterbird in relation to EU protected areas. *Diversity and Distributions*, 21(5), 571-582. <https://doi.org/10.1111/ddi.12300>
- Pearce-Higgins, J.W., Green, R.E. (2014). *Birds and Climate Change: Impacts and Conservation Responses*. Cambridge University Press, Cambridge. <https://www.cambridge.org/gb/academic/subjects/life-sciences/ecology-and-conservation/birds-and-climate-change-impacts-and-conservation-responses?format=PB#3XQeesBhMOwHXBLD.97>

- Pearce-Higgins, J.W., Beale, C.M., Oliver, T.H., August, T.A.; Carroll, M., Massimino, D. *et al.* (2017). A national-scale assessment of climate change impacts on species: assessing the balance of risks and opportunities for multiple taxa. *Biological Conservation*, 213, 124-134.
<http://doi.org/10.1016/j.biocon.2017.06.035>
- Perry, M., Vanvyve, E., Betts, R.A. and Palin, E.J. (2021). Past and future trends in fire weather for the UK. Submitted to *Natural Hazards and Earth System Sciences*
- Peschko, V., Mercker, M., Garthe, S. (2020). Telemetry reveals strong effects of offshore wind farms on behaviour and habitat use of common guillemots (*Uria aalge*) during the breeding season. *Marine Biology* 167, 118. <https://doi.org/10.1007/s00227-020-03735-5>
- Pessarrodona, A., Foggo, A., Smale, D.A. (2019). Can ecosystem functioning be maintained despite climate-driven shifts in species composition? Insights from novel marine forests. *Journal of Ecology*, 107, 91–104. <https://doi.org/10.1111/1365-2745.13053>
- Pettorelli, N., Smith, J., Pecl, G., Hill, J.K., Norris, K. (2019). Anticipating arrival: tacking the national challenges associated with the redistribution of biodiversity driven by climate change. *Journal of Applied Ecology*, 56(10), 2298 - 2304. <https://doi.org/10.1111/1365-2664.13465>
- Phelan, P., Morgan, E.R., Rose, H., Grant, J.; O’Kiely, P. (2016). Predictions of future grazing season length for European dairy, beef and sheep farms based on regression with bioclimatic variables. *Journal of Agricultural Science*, 154, 765–781. <https://doi.org/10.1017/S0021859615000830>
- Phillips, B.B., Shaw, R.F., Holland, M.J., Fry, E.L., Bardgett, R.D., Bullock, J.M., and Osborne, J.L. (2018). Drought reduces floral resources for pollinators. *Global Change Biology*, 24(7), 3226-3235.
<https://doi.org/10.1111/gcb.14130>
- Piccolroaz, S., Toffolon, M., Robinson, C.T., and Siviglia, A. (2018). Exploring and quantifying river thermal response to heatwaves. *Water*, 10(8), 1098. <https://doi.org/10.3390/w10081098>
- Pinnegar, J., Wright, P., Maltby, K., Garrett, A. (2020). Impacts of climate change on fisheries relevant to the coastal and marine environment around the UK. *MCCIP Science Review*, 456–481.
<https://doi.org/10.14465/2020.arc16.fsh>
- Piotrowska, M.J., Riddell, C., Hoebe, P., Ennos, R.A. (2018). Planting exotic relatives has increased the threat posed by *Dothistroma septosporum* to the Caledonian pine populations of Scotland. *Evolutionary Applications*, 11, 350 - 363. <https://doi.org/10.1111/eva.12562>
- Plantagenest, M., Le May, C., Fabre, F. (2007). Landscape epidemiology of plant diseases. *Journal of the Royal Society Interface*, 4, 963-972. <https://doi.org/10.1098/rsif.2007.1114>
- Platts, P.J., Mason, S.C., Palmer, G. (2019). Habitat availability explains variation in climate-driven range shifts across multiple taxonomic groups. *Scientific Reports*, 9, 15039.
<https://doi.org/10.1038/s41598-019-51582-2>
- Pollard, J.A., Spencer, T., Brooks, S.M. (2019). The interactive relationship between coastal erosion and flood risk. *Progress in Physical Geography: Earth and Environment*, 43, 574-585.
<https://doi.org/10.1177%2F0309133318794498>
- Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P.J. *et al.* (2013). Global Imprint of Climate Change on Marine Life. *Nature Climate Change*, 3(10), 919–925.
<https://doi.org/10.1038/nclimate1958>
- Pontee, N., Pye, K., Tempest, J., Blott, S. (2021). What is coastal squeeze? Final Report, Project FRS17187. Retrieved from <https://www.gov.uk/government/publications/what-is-coastal-squeeze>
- Poole, G.C., and Berman, C.H. (2001). An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-Caused Thermal Degradation. *Environmental Management* 27(6), 787–802 <https://doi.org/10.1007/s002670010188>

- Pope, E. *et al.* (2019). UK Food Security in a Changing Climate – Annual Report. Available from the Met Office on request
- Posthumus, H., Deeks, L.K., Rickson, R.J., Quinton, J.N. (2015). Costs and benefits of erosion control measures in the UK. *Soil Use and Management*, 31(51), 16-33. <https://doi.org/10.1111/sum.12057>
- Potopová, V., Lhotka, O., Možný, M., and Musiolková, M. (2020). Vulnerability of hop-yields due to compound drought and heat events over European key-hop regions. *International Journal of Climatology*. <https://doi.org/10.1002/joc.6836>
- Potter, C., Urquhart, J. (2017). Tree disease and pest epidemics in the Anthropocene: A review of the drivers, impacts and policy responses in the UK. *Forest Policy and Economics*, 79, 61-68. <https://doi.org/10.1016/j.forpol.2016.06.024>
- Poulain, F., Himes-Cornell, A.; Shelton, C. (2018). *Chapter 25: Methods and tools for climate change adaptation in fisheries and aquaculture* (FAO Fisheries and Aquaculture Technical Paper No. 627). https://www.academia.edu/37309127/Methods_and_tools_for_climate_change_adaptation_in_fisheries_and_aquaculture
- Poulton, P., Johnston, J., Macdonald, A., White, R., Powlson, D. (2018). Major limitations to achieving “4 per 1000” increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. *Global Change Biology*, 24, 2563-2584. <https://doi.org/10.1111/gcb.14066>
- Pow, R., Fletcher, R., Rink, M., Bradshaw, H., Clancy, E. (2020) Letter: Green Economic Recovery – The Water Industry’s Role in Building and Resilient Future. Defra, London https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/902487/green-recovery-letter-to-water-companies-200720.pdf
- Powney, G.D., Carvell, C., Edwards, M., Morris, R.K.A., Roy, H.E., Woodcock, B.A., and Isaac, N.J.B. (2019). Widespread losses of pollinating insects in Britain. *Nature Communications*, 10, 1018. <https://doi.org/10.1038/s41467-019-08974-9>.
- Priestley, M.D., Pinto, J.G., Dacre, H.F., Shaffrey, L.C. (2017). The role of cyclone clustering during the stormy winter of 2013/2014. *Weather*, 72(7), 187-192. <http://dx.doi.org/10.1002/wea.3025>
- Pritchard, O.G., Hallett, S.H., and Farewell, T.S. (2015). Probabilistic soil moisture projections to assess Great Britain’s future clay-related subsidence hazard. *Climatic Change*, 133(4), 635-650. <https://doi.org/10.1007/s10584-015-1486-z>
- Prober, S.M., Doerr, V.A., Broadhurst, L.M., Williams, K.J., Dickson, F. (2019). Shifting the conservation paradigm: A synthesis of options for renovating nature under climate change. *Ecological Monographs*, 89(1), e01333. <https://doi.org/10.1002/ecm.1333>
- Prudhomme, C., Haxton, T., Crooks, S., Jackson, C., Barkwith, A., Williamson, J., Kelvin, J., Mackay, J., Wang, L., Young, A., and Watts, G. (2013) Future Flows Hydrology: an ensemble of daily river flow and monthly groundwater levels for use for climate change impact assessment across Great Britain, *Earth Syst. Sci. Data*, 5, 101–107, <https://doi.org/10.5194/essd-5-101-2013>
- Pullens, J.W.M., Sharif, B., Trnka, M., Balek, J., Semenov, M.A., Olesen, J.E. (2019). Risk factors for European winter oilseed rape production under climate change. *Agricultural and Forest Meteorology*, 272-273, 30-39. <https://doi.org/10.1016%2Fj.agrformet.2019.03.023>
- Pywell, R. F., Heard, M. S., Woodcock, B. A., Hinsley, S., Ridding, L., Nowakowski, M., & Bullock, J. M. (2015). Wildlife-friendly farming increases crop yield: Evidence for ecological intensification. *Proceedings of the Royal Society B: Biological Sciences*, 282(1816), 20151740. <https://doi.org/10.1098/rspb.2015.1740>

- Qi, A., Holland, R.A., Taylor, G., Richter, G.M. (2018). Grassland futures in Great Britain – Productivity assessment and scenarios for land use change opportunities. *Science of the Total Environment*, 634, 1108–1118. <https://doi.org/10.1016/j.scitotenv.2018.03.395>
- Queirós, A.M., Fernandes, J., Genevier, L., Lynam, C.P. (2018). Climate change alters fish community size-structure, requiring adaptive policy targets. *Fish and Fisheries*, 19(4), 613–621. <https://doi.org/10.1111/faf.12278>
- Radbourne, A.D., Elliot, J.A., Maberly, S.C., Ryves, D.B., Anderson, N.J. (2019). The impacts of changing nutrient load and climate on a deep, eutrophic, monomictic lake. *Freshwater Biology*, 64(6), 1169–1182. <https://doi.org/10.1111/fwb.13293>
- Raseduzzaman, M., Jensen, E. (2017). Does intercropping enhance yield stability in arable crop production? A meta-analysis. *European Journal of Agronomy*, 91, 25 - 33. <http://dx.doi.org/10.1016/j.eja.2017.09.009>
- Ratcliffe, J., Andersen, R., Anderson, R., Newton, A., Campbell, D., Mauquoy, D. Payne, R. (2018). Contemporary carbon fluxes do not reflect the long-term carbon balance for an Atlantic blanket bog. *The Holocene*, 28, 140–149. <https://doi.org/10.1177%2F0959683617715689>
- Ray, D., Petr, M., Mullett, M., Bathgate, S., Marchi, M., Beauchamp, K. (2019). A simulation-based approach to assess forest policy options under biotic and abiotic climate change impacts: A case study on Scotland’s National Forest Estate. *Forest Policy and Economics*, 103, 17–27. <https://doi.org/10.1016/j.forpol.2017.10.010>
- Redhead, J.W., Oliver, T.H., Woodcock, B.A., Pywell, R.F. (2020). The influence of landscape composition and configuration on crop yield resilience. *Journal of Applied Ecology*, 57 (11). 2180-2190. <https://doi.org/10.1111/1365-2664.13722>
- Reed, K., Denman, S., Leather, S.R., Forster, J., and Inward, D.J.G. (2018). The lifecycle of *Agrilus biguttatus*: the role of temperature in its development and distribution, and implications for Acute Oak Decline. *Agricultural and Forest Entomology*, 20(3), 334-346. <http://doi:10.1111/afe.12266>
- Reed, K., Forster, J., Denman, S., Brown, N., Leather, S.R., Inward, D.J. (2020). Novel dendrochronological modelling demonstrates that decades of reduced stem growth predispose trees to Acute Oak Decline. *Forest Ecology and Management*, 476, 118441. Retrieved from <https://www.forestresearch.gov.uk/research/novel-dendrochronological-modelling-demonstrates-decades-reduced-stem-growth-predispose-trees-acute-oak-decline/>
- Reed, M., Courtney, P., Urquhart, J., Ross, N. (2013). Beyond fish as commodities: Understanding the socio-cultural role of inshore fisheries in England. *Marine Policy*, 7, 62–68. Retrieved from https://www.researchgate.net/publication/257163152_Beyond_fish_as_commodities_Understanding_the_socio-cultural_role_of_inshore_fisheries_in_England
- Régnier, T., Gibb, F.M., Wright P.J. (2017). Importance of trophic mismatch in a winter-hatching species: evidence from lesser sandeel. *Marine Ecology Progress Series*, 567, 185–197. <https://doi.org/10.3354/meps12061>
- Régnier, T., Gibb, F.M., Wright, P.J. (2019). Understanding temperature effects on recruitment in the context of trophic mismatch. *Science Reports* 9, 15179. <https://doi.org/10.1038/s41598-019-51296-5>
- Reinsch, S., Koller, E., Sowerby, A. et al. (2017), Shrubland primary production and soil respiration diverge along European climate gradient. *Sci. Rep.* 7, 43952. <https://doi.org/10.1038/srep43952>
- Reverter, M., Sarter, S., Caruso, D., Avarre, J.-C., Combe, M., Pepey, E. et al. (2020). Aquaculture at the crossroads of global warming and antimicrobial resistance. *Nature Communications*, 11. <https://doi.org/10.1038/s41467-020-15735-6>

- Rey, D., Holman, I.P., and Knox, J.W. (2017). Developing drought resilience in irrigated agriculture in the face of increasing water scarcity. *Regional Environmental Change*, 17(5), 1527-1540. <https://doi.org/10.1007/s10113-017-1116-6>
- Rezaei, E.E., Siebert, S., Hugging, H., Ewert, F. (2018). Climate change effect on wheat phenology depends on cultivar change. *Scientific Reports*, 8. <https://doi.org/10.1038/s41598-018-23101-2>
- Rhymes, J., Jones, L., Wallace, H., Jones, T.G., Dunn, C., Fenner, N. (2016). Small changes in water levels and groundwater nutrients alter nitrogen and carbon processing in dune slack soils. *Soil Biology and Biochemistry*, 99, 28-35. <https://doi.org/10.1016/j.soilbio.2016.04.018>
- Ricardo Energy & Environment. (2019). Carbon loss and economic impacts of a peatland wildfire in north-east Sutherland. Retrieved from https://www.wwf.org.uk/sites/default/files/2019-11/Carbon_loss_and_economic_impacts_of_a_peatland_wildfire_in_north-east_Sutherland.pdf
- Richardson, J., Miller, C., Maberly, S.C., Taylor, P., Globevnik, L., Hunter, P. *et al.* (2018). Effects of multiple stressors on cyanobacteria abundance vary with lake type. *Glob Chang Biol*, 24(11), 5044-5055. <https://doi.org/10.1111/gcb.14396>
- Rickson, R.J., Baggaley, N., Deeks, L.K., Graves, A., Hannam, J., Keay, C and Lilly, A. (2019). *Developing a method to estimate the costs of soil erosion in high-risk Scottish catchments. Report to the Scottish Government.* Retrieved from <https://www.gov.scot/ISBN/978-1-83960-754-7>
- Rigosi, A., Carey, C.C., Ibelings, B.W., Brookes, J.D. (2014). The interaction between climate warming and eutrophication to promote cyanobacteria is dependent on trophic state and varies among taxa. *Limnology and Oceanography*, 59, 99 -114. <https://doi.org/10.4319/lo.2014.59.1.0099>
- Riley, W.D., Potter, E.C.E.; Biggs, J., Collins, A.L., Jarvie, H.P., Jones, J.I. *et al.* (2018). Small Water Bodies in Great Britain and Ireland: Ecosystem function, human-generated degradation, and options for restorative action. *Science of the Total Environment* 645, 1598-1616. <https://doi.org/10.1016/j.scitotenv.2018.07.243>
- Rinde, E., Tjomsland, T., Hjermann, D.Ø., Kempa, M., Norling, P., Kolluru, V.S. (2017). Increased spreading potential of the invasive Pacific oyster (*Crassostrea gigas*) at its northern distribution limit in Europe due to warmer climate. *Marine and Freshwater Research*, 68(2), 252-262. <http://doi.org/10.1071/MF15071>
- Rio, M., Rey, D., Prudhomme, C., Holman, I.P. (2018). Evaluation of changing surface water abstraction reliability for supplemental irrigation under climate change. *Agricultural Water Management*, 206, 200-208. <https://doi.org/10.1016/j.agwat.2018.05.005>
- Ritchie, P.D.L., Harper, A.B., Smith, G.S., Kahana, R., Kendon, E.J., Lewis, H. *et al.* (2019). Large changes in Great Britain's vegetation and agricultural land-use predicted under unmitigated climate change. *Environmental Research Letters*, 14. <https://doi.org/10.1088/1748-9326/ab492b>
- Ritson, J.P., Brazier, R.E., Graham, N.J.D., Freeman, C., Templeton, M.R., Clark, J.M. (2017). The effect of drought on dissolved organic carbon (DOC) release from peatland soil and vegetation sources. *Biogeosciences*, 14(11), 2891–2902. <https://doi.org/10.5194/bg-14-2891-2017>
- Robins, P.E., Skov, M.W., Lewis, M.J., Gimenez, L., Davies, A.G., Malham, S.K. *et al.* (2015). Impact of climate change on UK estuaries: A review of past trends and potential projections. *Estuarine, Coastal and Shelf Science*, 169, 119-135. <https://doi.org/10.1016/j.ecss.2015.12.016>
- Robinson, D.A., Hopmans, J.W., Filipovic, V., van der Ploeg, M., Lebron, I., Jones, S.B. *et al.* (2019). Global environmental changes impact soil hydraulic functions through biophysical feedbacks. *Global Change Biology*, 25, 1895-1904. <https://doi.org/10.1111/gcb.14626>
- Robroek, B.J.M., Jassey, V.E.J., Payne, R.J. *et al.* (2017). Taxonomic and functional turnover are decoupled in European peat bogs. *Nature Commun.* 8, 1161. <https://doi.org/10.1038/s41467-017-01350-5>

- Rodríguez, A., Ruiz-Ramos, M., Palosuo, T., Carter, T.R., Fronzek, S., Lorite, I.J. *et al.* (2019). Implications of crop model ensemble size and composition for estimates of adaptation effects and agreement of recommendations. *Agricultural and Forest Meteorology*, 264, 351–362. <https://doi.org/10.1016/j.agrformet.2018.09.018>
- Rodríguez Valido, C.A., Johnson, M.F., Dugdale, S.J., Cutts, V., Fell, H.G., Higgins, E.A. *et al.* (2021). Thermal sensitivity of feeding and burrowing activity of an invasive crayfish in UK waters. *Ecohydrology*, 14, e2258. <https://doi.org/10.1002/eco.2258>
- Rogers, J., Loran, F. and Astle, G., (2008). National coastal erosion risk mapping the first national run. Proceedings 31st International Conference on Coastal Engineering, ASCE:4237-4249. https://doi.org/10.1142/9789814277426_0352
- Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T., Woznicki, S.A. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, 16, 145–163. <https://doi.org/10.1016/j.crm.2017.02.001>
- Rollet, A., and Williams, J. (2020a). Review of best practice for SOC monitoring Soil Policy Evidence Programme. (Welsh Government Report: SPEP 2019-20/05). Retrieved from <https://gov.wales/sites/default/files/publications/2020-11/review-best-practice-soil-organic-carbon-monitoring.pdf>
- Rollet, A., and Williams, J. (2020b). Assessment of Welsh Soil Issues in Context. Retrieved from <https://gov.wales/sites/default/files/publications/2020-11/assessment-soil-issues-in-context.pdf>
- Roman-Palacios, C., and Wiens, J.J. (2020). Recent responses to climate change reveal the drivers of species extinction and survival. *PNAS*, 117, 4211-4217. <https://doi.org/10.1073/pnas.1913007117>
- Roques, S.E., Kindred, D.R., Clarke, S. (2017). Triticale out-performs wheat on range of UK soils with a similar nitrogen requirement. *Journal of Agricultural Science*, 155(2), 261–281. <https://doi.org/10.1017/S0021859616000356>
- Rose, H., Caminade, C., Bolajoko, M.B., Phelan, P., van Dijk, J., Bayliss, M. *et al.* (2016). Climate-driven changes to the spatio-temporal distribution of the parasitic nematode, *Haemonchus contortus* in sheep in Europe. *Global Change Biology*, 22(3), 1271-1285. <https://doi.org/10.1111/gcb.13132>
- Rose, H., Wall, R. (2011). Modelling the impact of climate change on spatial patterns of disease risk: Sheep blowfly strike by *Lucilla sericata* in Great Britain. *International Journal for Parasitology* 41(7), 739-746. <https://doi.org/10.1016/j.ijpara.2011.01.012>
- Rose, S., and Rosolova, Z. (2015). *Energy crops and floodplain flows*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/480799/Energy_crops_and_floodplain_flows_report.pdf
- Roy, H.E., Bacher, S., Essl, F., Adriaens, T., Aldridge, D.C., Bishop, J.D. *et al.* (2019). Developing a list of invasive alien species likely to threaten biodiversity and ecosystems in the European Union. *Global Change Biology*, 25(3), 1032-1048. <https://doi.org/10.1111/gcb.14527>
- Roy, H.E., Peyton, J., Aldridge, D.C., Bantock, T., Blackburn, T.M., Britton, R. *et al.* (2014a). Horizon scanning for invasive alien species with the potential to threaten biodiversity in Great Britain. *Global Change Biology*, 20(12), 3859–3871. <https://doi.org/10.1111/gcb.12603>
- Roy, H.E., Preston, C.D., Harrower, C.A., Rorke, S.L., Noble, D., Sewell, J. *et al.* (2014b). GB Non-native Species Information Portal: documenting the arrival of non-native species in Britain. *Biological Invasions* 16(12), 2495–2505. <https://doi.org/10.1007/s10530-014-0687-0>
- Royal Forestry Society. (2019). *Bringing Woodland into management: The missed opportunities in England and Wales*. Retrieved from <https://www.rfs.org.uk/media/552717/woodland-management-missed-opportunities-in-england-and-wales.pdf>

- Royal Haskoning DHV. (2020). *Healthy Estuaries 2020: Towards Addressing Coastal Squeeze in Estuaries*. Retrieved from <http://publications.naturalengland.org.uk/publication/4734703644966912>
- Royal Society. (2020). Physical soil quality indicators for monitoring British soils. Retrieved from <https://royalsociety.org/-/media/policy/projects/soil-structures/soil-structure-evidence-synthesis-report.pdf>
- Royal Society. (2020). Soil structure and its benefits (ISBN: 978-1-78252-458-8). Retrieved from <https://royalsociety.org/topics-policy/projects/soil-structure-and-its-benefits/>
- RSA. (2020). *Our Future in the Land*. Retrieved from <https://www.thersa.org/discover/publications-and-articles/reports/future-land>
- RSPB. (2018). Bridging the finance gap. A discussion paper. Retrieved from <https://www.rspb.org.uk/globalassets/downloads/documents/abouttherspb/bridging-the-finance-gap.pdf>
- Rusch, A., Chaplin-Kramer, R., Gardiner, M.M., Hawro, V., Holland, J., Landis, D. *et al.* (2016). Agricultural landscape simplification reduces natural pest control: A quantitative synthesis. *Agriculture, Ecosystems & Environment*, 221, 198-204. <http://doi.org/10.1016/j.agee.2016.01.039>
- Rutterford, L.A., Simpson, S.D., Jennings, S., Johnson, M.P., Blanchard, J.L., Schön, P-J. *et al.* (2015). Future Fish Distributions Constrained by Depth in Warming Seas. *Nature Climate Change*, 5, 569–573. <https://doi.org/10.1038/nclimate2607>
- Salmaso, N., Zignin, A. (2010). At extreme of physical constraints: phytoplankton in highly flushed, large rivers. *Hydrobiologia*, 637, 12-36. <https://doi.org/10.1007/s10750-009-0018-0>
- Salmoral, G., Ababio, B., Holman, I.P. (2020). Drought Impacts, Coping Responses and Adaptation in the UK Outdoor Livestock Sector: Insights to Increase Drought Resilience. *Land*, 9(6), 202. <https://doi.org/10.3390/land9060202>
- Samplonius, J.M., Atkinson, A., Hassall, C., Keogan, K., Thackeray, S.J., Assmann, J.J. *et al.* (2021). Strengthening the evidence base for temperature-mediated phenological asynchrony and its impacts. *Nat Ecol Evol* 5, 155–164. <https://doi.org/10.1038/s41559-020-01357-0>
- Sayer, E.J., Oliver, A.E., Fridley, J.D., Askew, A.P., Mills, R.T.E., Grime, J.P. (2017). Links between soil microbial communities and plant traits in a species-rich grassland under long-term climate change. *Ecology and Evolution*, 7(3), 855–862. <https://doi.org/10.1002/ece3.2700>
- Sayers, P.B., Kay, A., Mauz, J., Horritt, M.S., Carr, S., Lamb, R., Penning-Rowsell, E. (2020). *UK Climate Change Risk Assessment 2022. Future flood risk. Report prepared for the Committee on Climate Change*. Retrieved from <https://www.ukclimaterisk.org/wp-content/uploads/2020/07/Future-Flooding-Main-Report-Sayers-1.pdf>
- Schloss, C.A., Nuñez, T.A., Lawler, J.J. (2012). Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. *Proceedings of the National Academy of Sciences of the United States of America*, 109(22), 8606–8611. <https://doi.org/10.1073/pnas.1116791109>
- Schils, R., Olesen, J.E., Kersebaum, K-C., Rijk, B., Oberforster, M., Kalyada, V. *et al.* (2018). Cereal yield gaps across Europe. *Eur. J. Agron.* 101, 109–120. <https://doi.org/10.1016/j.eja.2018.09.003>
- Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M. L., Wolff, C., Lincke, D. *et al.* (2018). Future response of global coastal wetlands to sea-level rise. *Nature*, 561(7722), 231-234. Retrieved from <https://doi.org/10.1038/s41586-018-0476-5>
- Scottish Forestry. (2014). Native Woodland Survey Scotland. Retrieved from <https://forestry.gov.scot/forests-environment/biodiversity/native-woodlands/native-woodland-survey-of-scotland-nwss>

- Scottish Government. (2019). Climate Ready Scotland: Second Scottish Climate Change Adaptation Programme 2019-2024. Retrieved from <https://www.gov.scot/publications/climate-ready-scotland-second-scottish-climate-change-adaptation-programme-2019-2024/>
- Scottish Government. (2020). Monitoring the socio-economic impacts of Marine Protected Areas: 2019 report. Retrieved from <https://www.gov.scot/publications/monitoring-socio-economic-impacts-marine-protected-areas/>
- Scottish Government. (2020a). Protecting Scotland, Renewing Scotland. Retrieved from <https://www.gov.scot/publications/protecting-scotland-renewing-scotland-governments-programme-scotland-2020-2021/>
- Scottish Government. (2020b). Monitoring the socio-economic impacts of Marine Protected Areas: 2019 report. Retrieved from <https://www.gov.scot/publications/monitoring-socio-economic-impacts-marine-protected-areas/>
- Scottish Natural Heritage. (2017). Scotland's Biodiversity Progress to 2020 Aichi Targets Interim Report 2017. Retrieved from https://www.nature.scot/sites/default/files/2018-05/Aichi_Report_Interim_2017.pdf
- Scottish Parliament Information Service. (2018). How are Fishing Quotas set? Retrieved from <https://spice-spotlight.scot/2018/10/08/how-are-fishing-quotas-set-stage-1-scientific-advice/>
- Searle, K., Butler, A., Bogdanova, M., Daunt, F. (2020). Scoping Study: Regional Population Viability Analysis for Key Bird Species CR/2016/16. *Scottish Marine and Freshwater Science* 11(10) <https://data.marine.gov.scot/dataset/scoping-study-regional-population-viability-analysis-key-bird-species-cr201616>
- Senapati, N. and Semenov, M.A. (2019). Assessing yield gap in high productive countries by designing wheat ideotypes. *Sci Rep* 9, 5516. <https://doi.org/10.1038/s41598-019-40981-0>
- SEPA. (2013). Managing Invasive Non-Native Species in Scotland's Water Environment: A summary of local actions. Retrieved from https://www.sepa.org.uk/media/37362/managing-invasive-non-native-species_plan.pdf
- Shackleton, R.T., Bertzky, B., Wood, L.E., Bunbury, N., Jäger, H., van Merm, R. *et al.* (2020). Biological invasions in World Heritage Sites: current status and a proposed monitoring and reporting framework. *Biodiversity and Conservation*, 29, 3327–3347. <https://doi.org/10.1007/s10531-020-02026-1>
- Sharples, J., Holt, J.; Wakelin, S. (2020). Impacts of climate change on shelf-sea stratification relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 103–115. <https://doi.org/10.14465/2020.arc05.str>
- Shephard, S., Beukers-Stewart, B., Hiddink, J.G., Brand, A.R., Kaiser, M.J. (2010). Strengthening recruitment of exploited scallops *Pecten maximus* with ocean warming. *Marine Biology*, 157(1), 91-97. <https://doi.org/10.1007/s00227-009-1298-7>
- Siebert, S., Webber, H.A., Rezaei, E.E (2017). Weather impacts on crop yields-searching for simple answers to a complex problem. *Environmental Research Letters*, 12, 081001. <https://doi.org/10.1088/1748-9326/aa7f15>
- Silbiger, N.J., Sorte, C.J.B. (2018). Biophysical feedbacks mediate carbonate chemistry in coastal ecosystems across spatiotemporal gradients. *Science Reports* 8, 796. <https://doi.org/10.1038/s41598-017-18736-6>
- Simon-Nutbrown, C., Hollingsworth, P.M., Fernandes, T.F., Kamphausen, L., Baxter, J.M., Burdett, H.L. (2020). Species Distribution Modeling Predicts Significant Declines in Coralline Algae Populations Under Projected Climate Change With Implications for Conservation Policy. *Frontiers in Marine Science*, 7, 575825. <https://doi.org/10.3389/fmars.2020.575825>

- Skaalsveen, K., Ingram, J., Clarke, L.E. (2019). The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: A literature review. *Soil and Tillage Research*, 189, 98-109. <https://doi.org/10.1016/j.still.2019.01.004>
- Skelsey, P., Cooke, D.E.L., Lynott, J.S., Lees, A.K. (2016). Crop connectivity under climate change: future environmental and geographic risks of potato late blight in Scotland. *Global Change Biology* 22(11), 3724-3738. <https://doi.org/10.1111/gcb.13368>
- Skelsey, P., Dancy, S.R., Preedy, K., Lees, A.K., Cooke, D.E.L. (2017). Forecasting the spread of aerially transmitted crop diseases with a binary classifier for inoculum survival. *Plant Pathology*, 67, 920 - 928. <https://doi.org/10.1111/ppa.12808>
- Skelsey, P., Kettle, H., MacKenzie, K., Blok, V. (2018). Potential impacts of climate change on the threat of potato cyst nematode species in Great Britain. *Plant Pathology* 67(4), 909-919. <https://doi.org/10.1111/ppa.12807>
- Skelsey, P., Newton, A.C. (2015). Future environmental and geographic risks of Fusarium head blight of wheat in Scotland. *European Journal of Plant Pathology*, 142(1), 133–147. <https://doi.org/10.1007/s10658-015-0598-7>
- Skuce, P.J., Morgan, E.R., Dijk, J., Van, Mitchell, M. (2013). Animal health aspects of adaptation to climate change: beating the heat and parasites in a warming Europe *Animal*, 7(s2), 333-345. <https://doi.org/10.1017/S175173111300075X>
- Slavik, K., Lemmen, C., Zhang, W., Kerimoglu, O., Klingbeil, K., Wirtz, K.W. (2019). The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea. *Hydrobiologia*, 845, 35-53. <https://doi.org/10.1007/s10750-018-3653-5>
- Slingo, J. (2021) Latest scientific evidence for observed and projected climate change. In: *The Third UK Climate Change Risk Assessment Technical Report* [Betts, R.A., Haward, A.B. and Pearson, K.V. (eds.)]. Prepared for the Climate Change Committee, London <https://www.ukclimaterisk.org/independent-assessment-ccra3/technical-report/>
- Smale, D.A. (2020). Impacts of ocean warming on kelp forest ecosystems. *New Phytologist*, 225(4), 1447-1454. <https://doi.org/10.1111/nph.16107>
- Smale, D., Moore, P., Queirós, A., Higgs, N., Burrows, M. (2018). Appreciating interconnectivity between habitats is key to blue carbon management. *Frontiers in Ecology and the Environment*, 16(2), 71-73. <https://doi.org/10.1002/fee.1765>
- Smale, D., Wernberg, T., Yunnice, A.L., Vance, T. (2015). The rise of *Laminaria ochroleuca* in the Western English Channel (UK) and comparisons with its competitor and assemblage dominant *Laminaria hyperborea*. *Marine Ecology Progress Series*, 36, 1033-1044. <https://doi.org/10.1111/maec.12199>
- Smith, I.P., Guy, C., Donnan, D. (2014). Pacific oysters, *Crassostrea gigas*, established in Scotland. *Aquat Conserv*, 25, 733-742. <https://doi.org/10.1002/aqc.2483>
- Smithers, R.J., Doick, K.J., Burton, A, Sibille, R, Steinbach, D, Harris, R. *et al.* (2018). Comparing the relative abilities of tree species to cool the urban environment. *Urban Ecosystems*, 21, 851–862. <https://doi.org/10.1007/s11252-018-0761-y>
- Smyth, D., Hayden-Hughes, M., Alexander, J., Bayford, P., Kregting, L. (2021). “Good news everyone”, the natives have returned: Assemblages of European flat oysters make a reappearance in Belfast Lough after a century of absence. *Regional Studies in Marine Science*, 41, 101585. <https://doi.org/10.1016/j.rsma.2020.101585>
- SNH. (2015). Scotland’s National Peatland Plan Working for our future. https://www.nature.scot/sites/default/files/2017-07/A1697542%20-%20150730%20-%20peatland_plan.pdf

- Solandt, J-L. (2018). A stocktake of England's MPA network—taking a global perspective approach. *Biodiversity*, 19(1-2), 34-41. <https://doi.org/10.1080/14888386.2018.1464950>
- Soteriades, A.D., Gonzalez-Mejia, A.M., Styles, D., Foskolos, A., Moorby, J.M., Gibbons, J.M. (2018). Effects of high-sugar grasses and improved manure management on the environmental footprint of milk production at the farm level. *Journal of Cleaner Production*, 202, 1241-1252. <https://doi.org/10.1016/j.jclepro.2018.08.206>
- Soussana, J.F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P. *et al.* (2019). Matching policy and science: Rationale for the '4 per 1000-soils for food security and climate' initiative. *Soil and Tillage Research*, 188, 3-15. <https://doi.org/10.1016/j.still.2017.12.002>
- South Downs National Park. (2020). *Climate Change Adaptation Plan*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/573931/climate-adrep-south-downs-national-park.pdf
- Souty-Grosset, C., Anastácio, P.M., Aquiloni, L., Banha, F., Choquer, J. *et al.* (2016). The red swamp crayfish *Procambarus clarkii* in Europe: Impacts on aquatic ecosystems and human well-being. *Limnologia*, 58, 78 - 93. <https://doi.org/10.1016/j.limno.2016.03.003>
- Spaans, F., Caruso, T., and Montgomery, I. (2018). The abundance and condition of hedgerow tree standards in Northern Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy*, 1188(3), 129-145. <https://doi.org/10.3318/bioe.2018.12>
- Spake, R., Bellamy, C.; Gill, R.; Watts, K.; Wilson, T.; Ditchburn, B.; Eigenbrod, F. (2020). Forest damage by deer depends on cross-scale interactions between climate, deer density and landscape structure. *Journal of Applied Ecology*, 57(7), 1376-1390. <https://doi.org/10.1111/1365-2664.13622>
- Spencer, T., Möller, I., Rupprecht, F., Bouma, T.J., van Wesenbeeck, B.K., Kudella, M. *et al.* (2015). Salt marsh surface survives true-to-scale simulated storm surges. *Earth Surface Processes and Landforms*, 41(4), 543-552. <https://doi.org/10.1002/esp.3867>
- Spencer, P. *et al.* (2018). The floods of December 2015 in northern England: description of the events and possible implications for flood hydrology in the UK. *Hydrological Processes*, 49(2), 568. <http://iwaponline.com/hr/article-pdf/49/2/568/196361/nh0490568.pdf>
- Spinoni, J., Vogt, J.V., Naumann, G., Barbosa, P., Dosio, A. (2018). Will drought events become more frequent and severe in Europe? *International Journal of Climatology*, 38(4), 1718-1736. <https://doi.org/10.1002/joc.5291>
- Spooner, T., Jones, A.E., Fearnley, J., Savani, R., Turner, J., Baylis, M. (2020). Bayesian optimisation of restriction zones for bluetongue control. *Sci Rep* 10, 15139. <https://doi.org/10.1038/s41598-020-71856-4>
- SRUC. (2013). Assessing the preparedness of England's natural resources for a changing climate: Assessing the type and level of adaptation action required to address climate risks in the 'vulnerability hotspots'. Final report to the CCC. <https://www.theccc.org.uk/publication/assessing-preparedness-englands-natural-resources-changing-climate-assessing-type-level-adaptation-action-required-address-climate-risks-vulnerabil/>
- State of Nature Partnership. (2019). State of Nature 2019. <https://jncc.gov.uk/news/uk-state-of-nature-2019-report/>
- Stebbing, P., McPherson, N., Ryder, D., and Jeffery, K. (2016). *Controlling invasive crayfish Managing signal crayfish populations in small enclosed water bodies* (C5775). Retrieved from <http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=18605&FromSearch=Y&Publisher=1&SearchText=crayfish&SortString=ProjectCode&SortOrder=Asc&Paging=10>

- Steele, D.J., Baldock, K.C.R., Breeze, T.D., Brown, M.J.F., Carvell, C., Dicks, L.V. *et al.* (2019). Management and drivers of change of pollinating insects and pollination services. National Pollinator Strategy: for bees and other pollinators in England, Evidence statements and Summary of Evidence. Retrieved from <http://centaur.reading.ac.uk/88315/>
- Stetkiewicz, S., Burnett, F.J., Ennos, R.A., Topp, C.F.E. (2019). The impact of fungicide treatment and Integrated Pest Management on barley yields: Analysis of a long term field trials database. *European Journal of Agronomy*, 105, 111 – 118. <https://doi.org/10.1016/j.eja.2019.02.010>
- Stockwell, J.D., Doubek, J.P., Adrian, R., Anneville, O., Carey, C.C., Carvalho, L. *et al.* (2020). Storm impacts on phytoplankton community dynamics in lakes. *Global Change Biology*, 26(5), 2756-2784. <https://doi.org/10.1111/gcb.15033>
- Stoekli, S., Felber, R., Haye, T. (2020). Current distribution and voltinism of the brown marmorated stink bug, *Halyomorpha halys*, in Switzerland and its response to climate change using a high-resolution CLIMEX model. *International Journal of Biometeorology* 64(12), 2019-2032. <https://doi.org/10.1007/s00484-020-01992-z>
- Straw, N.A., Fielding, N.J., Tilbury, C., Williams, D.T. and Cull, T. (2016). History and development of an isolated outbreak of Asian longhorn beetle *Anoplophora glabripennis* (Coleoptera: Cerambycidae) in southern England. *Agricultural and Forest Entomology*, 18: 280-293. <https://doi.org/10.1111/afe.12160>
- Suggitt, A.J., Wilson, R.J., Isaac, N.J.B., Beale, C.M., Auffret, A.G., August, T. *et al.* (2018). Extinction risk from climate change is reduced by microclimatic buffering. *Nature Climate Change*, 8, 713 - 717. <https://doi.org/10.1038/s41558-018-0231-9>
- Surminski, S. (2021) Business and industry. In: *The Third UK Climate Change Risk Assessment Technical Report* [Betts, R.A., Haward, A.B. and Pearson, K.V. (eds.)]. Prepared for the Climate Change Committee, London <https://www.ukclimaterisk.org/independent-assessment-ccra3/technical-report/>
- Sumner-Kalkun, J.C., Hight, F., Arnsdorf, Y.M., Back, E., Carnegie, M., Madden, S. *et al.* (2020). ‘Candidatus *Liberibacter solanacearum*’ distribution and diversity in Scotland and the characterisation of novel haplotypes from *Craspedolepta* spp. (Psyllidae: Aphalaridae). *Sci Rep* 10, 16567. <https://doi.org/10.1038/s41598-020-73382-9>
- Tainio, A., Heikkinen, R.K., Heliölä, J., Hunt, A., Leikola, N., Lötjönen, S., Mashkina, O., Watkiss, P and Carter T.R. (2014). Conservation of grassland butterflies in Finland under a changing climate. Regional Environmental Change. REC-D-13-00375. Published on-line 10th September 2014. <https://doi.org/10.1007/s10113-014-0684-y>
- Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., van der Heijden, M.G.A., Liebman, M., Hallin, S. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science advances*, 6(45), eaba1715. <https://doi.org/10.1126/sciadv.aba1715>
- Tang, R., Clark, J.M., Bond, T., Graham, N., Hughes, D., Freeman, C. (2013). Assessment of potential climate change impacts on peatland dissolved organic carbon release and drinking water treatment from laboratory experiments. *Environmental Pollution*, 173, 270-277. <https://doi.org/10.1016/j.envpol.2012.09.022>
- Teagle, H., and Smale, D.A. (2018). Climate-driven substitution of habitat-forming species leads to reduced biodiversity within a temperate marine community. *Diversity and Distributions*, 24(10), 1367-1380. <https://doi.org/10.1111/ddi.12775>

- Telford, A., Cavers, S., Ennos, R.A., Cottrell, J.E. (2015). Can we protect forests by harnessing variation in resistance to pests and pathogens? *Forestry*, 88, 3–12. <https://doi.org/10.1093/forestry/cpu012>
- Terrer, C., Jackson, R.B., Prentice, C., Keenan, T.F., Kaiser, C., Vicca, S. *et al.* (2019). Nitrogen and phosphorus constrain the CO₂ fertilization of global plant biomass. *Nature Climate Change* 9, 684–689. <https://doi.org/10.1038/s41558-019-0545-2>
- Thackeray, S., Henrys, P., Hemming, D., Bell, J.R., Botham, M.S., Burthe, S. *et al.* (2016). Phenological sensitivity to climate across taxa and trophic levels. *Nature*, 535, 241 - 245. <https://doi.org/10.1038/nature18608>
- Thackeray, S.J., Henrys, P.A., Feuchtmayr, H., Jones, I.D., Maberly, S.C., Winfield, W. (2013). Food web desynchronization in England's largest lake: an assessment based on multiple phenological metrics. *Global Change Biology*, 19(12), 3568-3580. <https://doi.org/10.1111/gcb.12326>
- Thackeray, S.J., Sparks, T.H., Frederiksen, M., Burthe, S., Bacon, P.J., Bell, J.R. *et al.* (2010). Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology* 16(12), 3304-3313. <https://doi.org/10.1111/j.1365-2486.2010.02165.x>
- The Grocer. (2019). What lies beneath: Fish category report 2019 Retrieved from <https://www.thegrocer.co.uk/category-reports/what-lies-beneath-fish-category-report-2019/599292.article>
- The Home Office. (2018). Biological Security Strategy. Retrieved from London: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/730213/2018_UK_Biological_Security_Strategy.pdf
- Thomas, P., Büntgen, U. (2018). First harvest of Périgord black truffle in the UK as a result of climate change *Climate Research*, 74, 67-70. <https://doi.org/10.3354/cr01494>
- Thompson, K., Miller, K., Johnston, P., Santillo, D. (2017). Storage of carbon by marine ecosystems and their contribution to climate change mitigation. Greenpeace Research Laboratories Technical Report 03-2017. Retrieved from <https://www.greenpeace.to/greenpeace/wp-content/uploads/2017/05/Carbon-in-Marine-Ecosystems-Technical-Report-March-2017-GRL-TRR-03-2017.pdf>
- Thompson, R.L., Broquet, G., Gerbig, C., Koch, T., Lang, M., Monteil, G. *et al.* (2020). Changes in net ecosystem exchange over Europe during the 2018 drought based on atmospheric observations. *Philosophical Transactions of the Royal Society B*, 375(1810), 20190512. <https://doi.org/10.1098/rstb.2019.0512>
- Tinker, J.P., Howes, E.L., Wakelin, S., Menary, M.B., Kent, E., Berry, D. *et al.* (2020). The impacts of climate change on temperature (air and sea), relevant to the coastal and marine environment around the UK. *MCCIP Science Review*, 1 - 3. <https://doi.org/10.14465/2020.arc01.tem>
- Tinsley, P. (2020). Marine protected areas in the UK – conservation or recovery? *In: Marine Protected Areas*. (eds): Humphreys, J. Clark, R.W.E. Elsevier.pp.217-236. <https://doi.org/10.1016/B978-0-08-102698-4.00012-5>.
- Townend, I. H., French, J. R., Nicholls, R. J., Brown, S., Carpenter, S., Haigh, I. D., Hill, C. T., Lazarus, E., Penning-Rowsell, E. C., Thompson, C. E. L., & Tompkins, E. L. (2021). Operationalising coastal resilience to flood and erosion hazard: A demonstration for England. *Science of the Total Environment*, 783, [146880]. <https://doi.org/10.1016/j.scitotenv.2021.146880>
- Townhill, B.L., Pinnegar, J.K., Righton, D.A., Metcalfe, J.D. (2017). Fisheries, Low Oxygen and Climate Change: How Much do we Really Know? *Journal of Fish Biology*, 90(3), 723–750. <https://doi.org/10.1111/jfb.13203>

- Tracy, A.M., Pielmeier, M.L.; Toshioka, R.M.; Heron, S.F.; Harvell, C.D. (2019). Increases and decreases in marine disease reports in an era of global change. *Proceedings of the Royal Society B*, 286(1912). <https://doi.org/10.1098/rspb.2019.1718>
- Tranvik, L.J., Downing, J.A., Cotner, J. B., Loiselle, S. A., Striegl, R.G., Ballatore, T.J. *et al.* (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and Oceanography*, 54(6 - 2), 2298-2314. https://doi.org/10.4319/lo.2009.54.6_part_2.2298
- Trnka, M., Hlavinka, P., Semenov, M.A. (2015). Adaptation options for wheat in Europe will be limited by increased adverse weather events under climate change *Journal of the Royal Society Interface*, 12(112). <https://doi.org/10.1098/rsif.2015.0721>
- Tröltzsch, J., McGlade, K., Voss, P., Tarpey, J., Abhold, K., Watkiss, P. *et al.* (2018). D1.2 Knowledge synthesis and gap analysis on climate impact analysis, economic costs and scenarios. Deliverable to the COACCH project. Retrieved from https://www.ecologic.eu/sites/files/publication/2019/2811-d1_2-coacch-research-gap-report.pdf
- Tschakert, P., Ellis, N.R., Anderson, C., Kelly, A., Obeng, J. (2019). One thousand ways to experience loss: A systematic analysis of climate-related intangible harm from around the world. *Global Environmental Change*, 55, 58-72. <https://doi.org/10.1016/j.gloenvcha.2018.11.006>
- Tsiamis, K., Azzurro, E., Bariche, M., Çinar, M.E., Crocetta, F., De Clerck, O. *et al.* (2020). Prioritizing marine invasive alien species in the European Union through horizon scanning. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 30(4), 794-845. <https://doi.org/10.1002/aqc.3267>
- UK Groundwater Forum (1998) Groundwater – Our Hidden Asset. British Geological Survey. <http://www.groundwateruk.org/forum-assetbook-hidden-asset.aspx>
- UK Parliament POST. (2019). Climate Change and UK Wildfire. Retrieved from <https://post.parliament.uk/research-briefings/post-pn-0603/>
- UNESCO. (2003). Cultural landscapes: the challenges of conservation. Retrieved from <https://unesdoc.unesco.org/ark:/48223/pf0000132988>
- Unterberger, C., Brunner, L., Nabernegg, S., Steininger, K.W., Steiner, A.K., Stabentheiner, E. *et al.* Monschein, S., Truhetz, H. (2018). Spring frost risk for regional apple production under a warmer climate. *PLoS one* 13(7), e0200201. <https://doi.org/10.1371/journal.pone.0200201>
- Valdivia-Garcia, M., Weir, P., Graham, D.W., Werner, D. (2019). Predicted Impact of climate change on trihalomethanes formation in drinking water treatment. *Scientific Reports*, 9(1), 1-10. <https://doi.org/10.1038/s41598-019-46238-0>
- van Buuren, A., Lawrence, J., Potter, K., Warner, J.F. (2018). Introducing adaptive flood risk management in England, New Zealand, and the Netherlands: The impact of administrative traditions. *Review of Policy Research*, 35(6), 907-929. <https://doi.org/10.1111/ropr.12300>
- van der Kooij, J., Engelhard, G.H., Righton, D.A. (2016). Climate change and squid range expansion in the North Sea. *Journal of Biogeography*, 43(11), 2285-2298. <https://doi.org/10.1111/jbi.12847>
- Van der Veken, S., Hermy, M., Vellend, M., Knapen, A., Verheyen, K. (2008). Garden plants get a head start on climate change. *Frontiers in Ecology and the Environment* 6, 212–216. <https://doi.org/10.1890/070063>
- van Gestel, N., Shi, Z., van Groenigen, K.J., Osenberg, C.W., Andresen, L.C., Dukes, J.S. *et al.* (2018). Predicting soil carbon loss with warming. *Nature*, 554, E4-E5. <https://doi.org/10.1038/nature25745>
- van Groenigen, J.W., Lubbers, I.M., Vos H.M.J., Brown, G.G., De Deyn G.B., van Groenigen, K.J. (2015). Earthworms increase plant production: a meta-analysis. *Scientific Reports*, 4, 6365. <https://doi.org/10.1038/srep06365>

- van Katwijk, M.M., Thorhaug, A., Marbà, N., Orth, R.J., Duarte, C.M., Kendrick, G.A. *et al.* (2016). Global review of seagrass restoration and the importance of large-scale planting. *Journal of Applied Ecology*, 53, 567–578. <https://doi.org/10.1111/1365-2664.12562>
- Van Laer, E., Moons, C.P.H., Sonck, B., Tuytens, F.A.M. (2014). Importance of outdoor shelter for cattle in temperate climates. *Livestock Science*, 159(1), 87–101. <https://doi.org/10.1016/j.livsci.2013.11.003>
- Van Laer, E., Tuytens, F.A.M., Ampe, B., Sonck, B., Moons, C.P.H., Vandaele, L. (2015). Effect of summer conditions and shade on the production and metabolism of Holstein dairy cows on pasture in temperate climate. *Animal*, 9, 1547–1558. <https://doi.org/10.1017/S1751731115000816>
- Vanbergen, A.J. (2014). Landscape alteration and habitat modification: impacts on plant–pollinator systems. *Curr Opin Insect Sci*, 5, 44-49. <https://doi.org/10.1016/j.cois.2014.09.004>
- Vanbergen, A.J., Espindola, A., Aizen, M.A. (2018). Risks to pollinators and pollination from invasive alien species. *Nature Ecology & Evolution*, 2(1), 16-25. <https://doi.org/10.1038/s41559-017-0412-3>
- Vaughan, I., and Ormerod, S.J. (2012). Large-scale, long-term trends in British river Macroinvertebrates. *Global Change Biology* 18(7), 2184-2194. <https://doi.org/10.1111/j.1365-2486.2012.02662.x>
- Vaughan, I.P., and Gotelli, N.J. (2019). Water quality improvements offset the climatic debt for stream macroinvertebrates over twenty years. *Nature Communications*, 10, 1956 (2019). <https://doi.org/10.1038/s41467-019-09736-3>
- Vaughan, I.P., and Ormerod, S.J. (2014). Linking interdecadal changes in British river ecosystems to water quality and climate dynamics. *Global Change Biology*, 20(9), 2725–2740. <https://doi.org/10.1111/gcb.12616>
- Veng, T. and Andersen, O.B. 2020. Consolidating sea level acceleration estimates from satellite altimetry. *Advances in Space Research*, in press. <https://doi.org/10.1016/j.asr.2020.01.016>
- Verberk, W.C.E.P. Durance, I., Vaughan, I. P., Ormerod, S.J. (2016). Field and laboratory studies reveal interacting effects of stream oxygenation and warming on aquatic ectotherms. *Global Change Biology*, 22(5), 1769-1778. <https://doi.org/10.1111/gcb.13240>
- Verrillo, F., Badeck, F., Terzi, V., Rizza, F., Bernardo, L., Di Maro, A. *et al.* (2017). Elevated field atmospheric CO₂ concentrations affect the characteristics of winter wheat (cv. Bologna) grains. *Crop & Pasture Science*, 68, 713–725. <https://doi.org/10.1071/CP17156>
- Vindenes, Y., Edeline, E., Ohlberger, J., Langangen, Ø., Winfield, I.J.; Stenseth, N.C. *et al.* (2014). Effects of Climate Change on Trait-Based Dynamics of a Top Predator in Freshwater Ecosystems. *The American Naturalist*, 183(2), 243-256. Retrieved from <https://www.journals.uchicago.edu/doi/pdfplus/10.1086/674610>
- Wainwright, C., Jenkins, S., Wilson, D., Elliott, M., Jukes, A., and Collier, R. (2020). Phenology of the Diamondback Moth (*Plutella xylostella*) in the UK and Provision of Decision Support for Brassica Growers. *Insects*, 11(2), 118. <https://doi.org/10.3390/insects11020118>
- Walkden, M., Watson, G., Johnson, A., Heron, E., Tarrant, O. (2016). Coastal catch-up following defence removal at Happisburgh. In *Coastal Management* (pp. 523–532). London, UK: ICE Publishing. <https://doi.org/10.1680/cm.61149.523>
- Wang, Z.B., and Townend, I.H. (2012). Influence of the nodal tide on the morphological response of estuaries. *Marine Geology*, 291, 73-82. <https://doi.org/10.1016/j.margeo.2011.11.007>
- Wanless, S., Harris, M.P., Newell, M.A., Speakman, J.R. and Daunt, F. (2018). Community-wide decline in the occurrence of lesser sandeels *Ammodytes marinus* in seabird chick diets at a North Sea colony. *Marine Ecology Progress Series*, 600, 193-206. <https://doi.org/10.3354/meps12679>

- Waser, A.M., Deuzeman, S., wa Kangeri, A.K., van Winden, E., Postma, J., de Boer, P. *et al.* (2016). Impact on bird fauna of a non-native oyster expanding into blue mussel beds in the Dutch Wadden Sea. *Biological Conservation*, 202, 39-49. <https://doi.org/10.1016/j.biocon.2016.08.007>
- Watkiss, P., Cimato, F., Hunt, A., Moxey, A. (2019). The Impacts of Climate Change on Meeting Government Outcomes in England. Report to the UK Committee on Climate Change (CCC). Retrieved from <https://www.theccc.org.uk/publication/impacts-of-climate-change-on-meeting-government-outcomes-in-england-paul-watkiss-associates/>
- Watkiss, P. and Betts, R.A. (2021) Method. In: *The Third UK Climate Change Risk Assessment Technical Report* [Betts, R.A., Haward, A.B. and Pearson, K.V. (eds.)]. Prepared for the Climate Change Committee, London <https://www.ukclimaterisk.org/independent-assessment-ccra3/technical-report/>
- Watkiss P and Hunt A (2018). Costs and Benefits of Adaptation: “Economic Appraisal of Adaptation Options for the Agriculture Sector. In. Economic Tools and Methods for the Analysis of Global Change Impacts on Agriculture and Food Security. Editor. Quiroga. S. Published by Springer. ISBN 978-3-319-99462-8. <https://doi.org/10.1007/978-3-319-99462-8>
- Watts, G.; Anderson, M. (eds) (2016). Water climate change impacts report card 2016 edition. Living With Environmental Change. ISBN 978-0-9934074-1-3. <https://nerc.ukri.org/research/partnerships/ride/lwec/report-cards/water/>
- Watts, K., Whytock, R.C., Park, K.J., Fuentes-Montemayor, E., Macgregor, N. A., Duffield, S., McGowan, P.J. (2020). Ecological time lags and the journey towards conservation success. *Nature Ecology & Evolution*, 4(3), 304-311. <http://hdl.handle.net/1893/30756>
- Webster, E., Cameron, R.W.F., Culham, A. (2017). Gardening in a Changing Climate. Retrieved from UK: <https://www.rhs.org.uk/science/pdf/RHS-Gardening-in-a-Changing-Climate-Report.pdf>
- Wells, M.L., Trainer, V.L., Smayda, T.J., Karlson, B.S.O., Trick, C.G., Kudela, R.M. *et al.* (2015). Harmful algal blooms and climate change: learning from the past and present to forecast the future. *Harmful Algae*, 49, 68– 93. <https://doi.org/10.1016/j.hal.2015.07.009>
- Welsh Government. (2018a). Woodlands for Wales. Retrieved from https://gov.wales/sites/default/files/publications/2018-06/woodlands-for-wales-strategy_0.pdf
- Welsh Government (2018b). Action Plan for Pollinators: Review 2013-18 and Future Actions. Retrieved from <https://gov.wales/sites/default/files/publications/2019-04/action-plan-for-pollinators-review-and-future-actions-en.pdf>
- Welsh Government. (2019a). Grassland fires, 2018-19 (Statistical Bulletin, SB49/2019). Retrieved from <https://gov.wales/sites/default/files/statistics-and-research/2019-10/grassland-fires-april-2018-march-2019-751.pdf>
- Welsh Government. (2019b). Prosperity for all: Climate Conscious Wales. Retrieved from <https://gov.wales/prosperity-all-climate-conscious-wales>
- Welsh Government. (2019c). *Prosperity for All: Climate Conscious Wales. Technical Annex*. Retrieved from <https://gov.wales/prosperity-all-climate-conscious-wales>
- Welsh Government. (2019d). Welsh National Marine Plan. Retrieved from https://gov.wales/sites/default/files/publications/2019-11/welsh-national-marine-plan-document_0.pdf
- Welsh Government. (2020). The National Strategy for Flood and Coastal Risk Management in Wales. Retrieved from <https://gov.wales/sites/default/files/publications/2020-11/the-national-strategy-for-flood-and-coastal-erosion-risk-management-in-wales.pdf>
- Welsh Water. (2018). Welsh Water 2050. Consultation Summary. Retrieved from <https://corporate.dwrcymru.com/en/about-us/our-plans/water-2050>

- Welsh Water. (2019). Final Water Resources Management Plan 2019. Retrieved from <https://www.dwrcymru.com/en/our-services/water/water-resources/final-water-resources-management-plan-2019>
- Welsh Water. (2020). Making Time for Nature. Retrieved from <https://corporate.dwrcymru.com/en/community/environment>
- Wendelboe, C., Kelly, S., Kennedy, M., Cherrie, J.W. (2019). A scoping review of mapping research on green space and associated mental health benefits. *International Journal of Environmental Research and Public Health*, 16(12), 2081. <https://dx.doi.org/10.3390%2Fijerph16122081>
- White, S., Bullock, J., Cavers, S., Chapman, D. (2019). Using modelling to investigate the effectiveness of national surveillance monitoring aimed at detecting a *Xylella fastidiosa* outbreak in Scotland. (CEH Project no. C07074). Retrieved from Invergowrie: <https://www.planthealthcentre.scot/publications/using-modelling-investigate-effectiveness-national-surveillance-monitoring-aimed>
- White, S., Falzon, C., Bell, H. (2020). Communicating landscape change from adaptation and mitigation in a changing climate (NRW Report No: 396). Retrieved from Bangor: <https://www.whiteconsultants.co.uk/wp-content/uploads/2020/04/Communicating-landscape-change-final-report-310320r.pdf>
- Whittet, R., Cavers, S., Ennos, R., Cottrell J. (2019). Genetic considerations for provenance choice of native trees under climate change in England. Forestry Commission Research Report. Retrieved from <https://www.forestresearch.gov.uk/research/genetic-considerations-provenance-choice-native-trees-under-climate-change-england/>
- Wignall, R.M., Gordon, J.E., Brazier, V., MacFadyen, C.C., Everett, N.S. (2018). A climate change risk-based assessment for nationally and internationally important geoheritage sites in Scotland including all earth science features in Sites of Special Scientific Interest (SSSI). *Proceedings of the Geologists' Association*, 192(2), 120-134. <https://www.nature.scot/sites/default/files/2018-04/Publication%202018%20-%20SNH%20Research%20%20Report%201014%20-%20A%20climate%20change%20risk-based%20assessment%20for%20nationally%20and%20internationally%20important%20geoheritage%20site%20in%20Scotland>
- Wilby, R.L., and Johnson, M.F. (2020). Climate variability and implications for keeping rivers cool in England. *Climate Risk Management* 30, 100259. <https://doi.org/10.1016/j.crm.2020.100259>
- Wilby, R.L., Johnson, M.F., Toone, J.A. (2015). Thermal shockwaves in an upland river. *Weather*, 70, 92-100 <https://doi.org/10.1002/wea.2435>
- Williams, F., Eschen, R., Harris, A., Djeddour, D., Pratt, C., Shaw, R.S. *et al.* (2010). The Economic Costs of Invasive Non-Native Species on Great Britain (CABI Report CAB/001/09). Retrieved from <https://www.cabi.org/VetMedResource/ebook/20123122024>
- Willing, M.J. (2015). Two invasive bivalves, *Rangia cuneata* (B. Sowerby I, 1831) and *Mytilopsis leucophaeata* (Conrad, 1831), living in freshwater in Lincolnshire, Eastern England. *Journal of Conchology*, 42(2), 189-192. <https://www.scopus.com/record/display.uri?eid=2-s2.0-84949514720&origin=inward&txGid=a4f1c802f43af22fe4887b6862e07014>
- WineGB. (2018). Looking to the future: The WineGB trade survey results 2018. Retrieved from <https://www.winegb.co.uk/wp-content/uploads/2018/06/WineGB-Industry-Report-April-2018.pdf>
- Winfield, I.J. (2016). Recreational fisheries in the UK: natural capital, ecosystem services, threats, and management. *Fisheries Science*, 82, 203–212. <https://doi.org/10.1007/s12562-016-0967-y>

- Winfield, I.J., Hateley, J., Fletcher, J.M., James, J.B., Bean, C.W., Clabburn, P. (2010). Population trends of Arctic charr (*Salvelinus alpinus*) in the UK: assessing the evidence for a widespread decline in response to climate change. *Hydrobiologia*, 650, 55–65. <https://doi.org/10.1007/s10750-009-0078-1>
- Wolf, J., Woolf, D., Bricheno, L. (2020). Impacts of climate change on storms and waves relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 132–157. Retrieved from http://www.mccip.org.uk/media/2010/07_storms_waves_2020.pdf
- Woodland Trust. (2016). *Keeping Rivers Cool: A Guidance Manual*. Retrieved from <https://www.woodlandtrust.org.uk/media/1761/keeping-rivers-cool.pdf>
- Woods, A.J., Martin-Garcia, J., Bulman, L., Vasconcelos, M.W., Boberg, J., La Porta, N. *et al.* (2016). Dothistroma needle blight, weather and possible climatic triggers for the disease's recent emergence. *Forest Pathology*, 46(5), 443-452. <https://doi.org/10.1111/efp.12248>
- Woodward, G., Bonada, N., Feeley, H.B., and Giller, P.S. (2015). Resilience of a stream community to extreme climatic events and long-term recovery from a catastrophic flood. *Freshwater Biology*, 60(12), 2497-2510. <https://doi.org/10.1111/fwb.12592>
- Woolway, R.I., Simpson, J.H., Spiby, D., Feuchtmayr, H., Powell, B., Maberly, S.C. (2018). Physical and chemical impacts of a major storm on a temperate lake: a taste of things to come? *Climate Change*, 151, 333–347. <https://doi.org/10.1007/s10584-018-2302-3>
- World Museum Liverpool. (2016). The status of the Snowdon Beetle *Chrysolina cerealis* on Yr Wyddfa in 2015 (NRW Evidence Report No: 160). Retrieved from Bangor: <https://cdn.naturalresources.wales/media/685039/report-193-status-snowdon-beetle-chrysolina-cerealis-yr-wyddfa-2016.pdf>
- Wreford, A., Moran, D., Moxey, A., Evans, K.A., Fox, N., Glenk, K. *et al.* (2015). Estimating the Costs and Benefits of Adapting Agriculture to Climate Change. *EuroChoices*, 14(2), 16-23. <https://doi.org/10.1111/1746-692X.12086>
- Wreford, A., Renwick, A. (2012). Estimating the costs of climate change adaptation in the agricultural sector. *CAB Reviews Perspectives in Agriculture Veterinary Science Nutrition and Natural Resources* 7,40. <https://doi.org/10.1079/PAVSNNR20127040>
- Wreford, A., Topp, C.F.E. (2020). Impacts of climate change on livestock and possible adaptations: A case study of the United Kingdom. *Agricultural Systems*, 178, 102737. <https://doi.org/10.1016/j.agsy.2019.102737>
- Wright, P., Pinnegar, J., Fox, C. (2020). Impacts of climate change on fish, relevant to the coastal and marine environment around the UK. *MCCIP Science Review*, 354–381. Retrieved from http://www.mccip.org.uk/media/2019/16_fish_2020.pdf
- WSP. (2019). Interacting Risks in infrastructure and the built and natural environments. Report to the Climate Change Committee. Retrieved from https://www.ukclimaterisk.org/wp-content/uploads/2020/07/Interacting-Risks_WSP.pdf
- Xu, J., Morris, P.J.; Liu, J.; Ledesma, J.L.J.; Holden, J. (2020). Increased Dissolved Organic Carbon Concentrations in Peat-Fed UK Water Supplies Under Future Climate and Sulfate Deposition Scenarios. *Water Resources Research*, 56(1). <https://doi.org/10.1029/2019WR025592>
- Yawson, D.O., Adu, M.O., Armah, F.A. (2020). Impacts of climate change and mitigation policies on malt barley supplies and associated virtual water flows in the UK. *Scientific Reports*, 10. <https://doi.org/10.1038/s41598-019-57256-3>
- Yawson, D.O., Mulholland, B.J., Ball, T., Adu, M.O., Mohan, S., White, P.J. (2018). Effect of climate and agricultural land use changes on UK feed barley production and food security to the 2050s. *Land*, 6, 74. <https://doi.org/10.3390/land6040074>

- Zampieri, M., Ceglar, A., Dentener, F. and Toreti, A. (2017). Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. *Environ. Res. Lett.* 12 064008. <https://iopscience.iop.org/article/10.1088/1748-9326/aa723b>
- Zhang, M., Dai, Z.; Bouma, T.J.; Bricker, J.; Townend, I.; Wen, J.; Zhao, T.; Cai, H. (2021). Tidal-flat reclamation aggravates potential risk from storm impacts. *Coastal Engineering*, 166, 103868. <https://doi.org/10.1016/j.coastaleng.2021.103868>
- Zhu, X., Linham, M.M., Nicholls, R.J. (2010). Technologies for climate change adaptation – coastal erosion and flooding. UNEP report. Denmark: Danmarks Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi. <https://www.osti.gov/etdeweb/biblio/1010716>
- Zurek, M., Garbutt, G., Lieb, T., Hess, T., Ingram, J. (2020). Increasing resilience of the UK fresh fruit and vegetable system to water-related risks. *Sustainability*, 12(18), 7519. <https://doi.org/10.3390/su12187519>