# Climate driven threshold effects in the natural environment

Report to the Climate Change Committee

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# Executive Summary

The aims of this project are to provide improved evidence of possible climate risks in the natural environment that do not follow linear patterns of change, assess the resulting impacts of these effects on different areas of society (e.g. communities, industries, workforces), identify what aspects of society are most at risk, and assess the extent to which current and potential future adaptation strategies can address the risk, either through preventing the threshold impact from occurring or managing the impact when it does.

Specifically, the project sets out to answer six questions:

1. What climate hazard thresholds represent points beyond which the effective functioning of key systems within the natural environment may be compromised, and why?
2. What are the resulting impacts on the goods and services provided to society from the natural environment? What would be the quantified impact?
3. Is there a risk of irreversible change in the ecosystems affected, or substantial time lags in recovery?
4. What is the impact of current levels of adaptation at mitigating these risks?
5. What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?
6. In what scenarios are there limits to adaptation?

The project followed three phases. The first phase was a literature review, conducted as a series of rapid evidence reviews, by habitat, to identify non-linear impacts which might occur in the UK. The second phase was a national screening assessment on a prioritised set of thresholds identified from the literature reviews. The screening assessment was conducted at national level, but with regional differentiation of the impacts. To investigate indicative impacts, these were quantified for baseline, and under 2 °C and 4 °C scenarios (independent of time), for a single climate model run. The third phase was a case study assessment which focused on a subset of impacts in more detail, drawing on climate data from 28 climate model projections provided by the UK Met Office. The case study assessments calculated a timeline of impacts to the end of the century, and produced summaries of impacts at baseline, the 2050s and the 2080s.

The rapid evidence reviews were conducted on five broad habitat types: freshwaters, farmland, peatlands, woodland, and marine and coastal margins. The reviews identified 37 potential impacts, which were scored against a set of criteria to identify a shorter list to take forward. Following the scoring, a list of 12 potential impacts were identified for the national screening assessment. Four of these impacts were then further developed in case studies. The need to prioritise down the number of thresholds for detailed analysis reflected resource constraints for the project rather than the importance of the thresholds. Some potentially important thresholds were not taken forward for assessment, such as temperature effects on salmonid fish in rivers.

The majority of these impact types had previously been identified in CCRA2. However, many only received cursory mention, and had not been explored with respect to the potential for non-linear responses, either in the magnitude of response, or the timing of when a response may occur. Where previous studies cited in CCRA2 had quantified some impact, there was usually no indication of the trajectory of change.

The key findings relevant to each of the questions are summarised below.

**What climate hazard thresholds represent points beyond which the effective functioning of key systems within the natural environment may be compromised, and why?**

The thresholds identified in the national screening assessment are summarised in Table ES1. Eleven of the twelve thresholds relate to temperature, and of those, one relates to temperature + rainfall in combination. The other is related to rainfall alone.

A variety of mechanisms govern how the thresholds are manifested. They include: physiological controls acting at a species level (spawning of shellfish, impacts on milk yield of dairy cattle), climatic limits on growth or survival of individual species (livestock parasites completing their life-cycle, survival of the freshwater fish Vendace), competition mediated impacts on community assembly or overall habitat climate envelope (zooplankton and phytoplankton communities in lakes, condition of peatlands).

In many cases, all or parts of the UK currently exceed the identified threshold, and are already experiencing greater ecological or economic impacts as a result. For example, the threshold water temperature governing change in zooplankton community composition in lakes is already exceeded in all regions of the UK.

The case studies show that the time at which the threshold is crossed can demonstrate considerable variation across the UK over the course of this century. In general, temperature thresholds are exceeded first in the south and east of England, moving progressively west and north, with north Scotland being the last to exceed the threshold. Across all the thresholds assessed in this study, at least one part of the UK exceeds the threshold by the 2080s.

**What are the resulting impacts on the goods and services provided to society from the natural environment? What would be the quantified impact?**

The impacts on goods and services, or other societal end-points of value such as biodiversity are summarised in Table ES1 for the screening assessment, and Table ES2 for the case studies. They cover provisioning services (milk yield, lamb production, timber production, wheat yield, general crop yield, fish & shellfish habitat range), regulating services (water quality, greenhouse gas emissions) and cultural services (recreation), as well as biodiversity.

Impacts are quantified in monetary terms, where possible, to understand the relative magnitude of threshold impacts, using both market and non-market valuation techniques. The impacts are presented as annual figures so that impacts can be compared for representative years under current conditions and in the future. It was not possible to calculate all impacts in economic terms, and some are expressed as increased magnitude or frequency of exceeding a climate threshold, or a change in an ecological variable. For example, the expansion of Pacific oyster is quantified as the viable area for spawning and reproduction, since it was not feasible to value the economic impacts of its spread.

This study does not aim to estimate the difference between economic impacts under linear versus threshold behaviour. Instead, it aims to show the time course of impacts as they are projected to develop under future climate trajectories, and to quantify those impacts under specified future conditions or time points, assuming that current adaptation is held constant. This approach was taken in order to identify shortfalls in adaptation and, using the case studies, to show the likely timelines of impact.

Economic impacts due to threshold exceedance varied from a few million to several billion (Tables ES1 and ES2). Impacts were in the tens of millions for temperature effects on milk production, timber production, and wheat production, and for rainfall effects on soil erosion. The latter only counted direct yield losses, whereas if associated effects on flooding, greenhouse gas emissions were counted the impacts would be much greater. Impacts in the hundreds of millions are likely to occur for temperature effects on algal blooms in lakes, and on parasites in lambs. Impacts rise into the billions towards the end of the century for temperature effects on greenhouse gas emissions from peatlands.

In the majority of impacts, the ecological or economic impact at least doubles from current day to the 2080s. In cases such as peatland carbon emissions, the economic impacts in the 2080s are almost ten times greater than current day.

**Is there a risk of irreversible change in the ecosystems affected, or substantial time lags in recovery?**

Risk of irreversible change for each threshold is summarised in Table ES3. For some, exceedance is short-lived, impacts are reversible and recovery can occur within days. An example being loss of milk production in dairy cattle during hot days. For other thresholds, impacts occur within a calendar year, but are unlikely to carry over to the next year. For example in annual crops where wheat yield is affected by high temperatures during flowering and grain filling in spring and early summer. Other impacts are effectively irreversible or can take many decades to recover. When topsoil is lost through erosion, this is a permanent loss of the soil natural capital. When peatlands become degraded, it can take many decades to restore natural function through re-wetting. In heavily gullied peatlands, recovery to a fully functioning peatland actively sequestering carbon is highly unlikely. In woodland, the effect of warming temperatures and drought on timber quality, and associated pests and diseases, means that some of the tree species currently growing could lose part or all of their economic value. In marine systems, range shifts or expansion of non-native species are very difficult to keep in check.

**What is the impact of current levels of adaptation at mitigating these risks?**

In most habitats, current levels of adaptation exhibit a shortfall, shown in Table ES3 and summarised below (with more detail in the specific chapter sections):

- In freshwaters, adaptation mainly hinges on nutrient management, which is the principal contributing factor to algal bloom development and other related ecological effects. This includes diffuse nutrients from catchments as well as from waste water discharge. There is management of nitrogen use in Nitrate Vulnerable Zones, but not widely elsewhere, and the interactions with climate are not widely acknowledged. There are currently no plans in place that address risks from higher water temperatures.
- In farmland and grassland, adaptation measures are not widely practiced or the challenge is not currently deemed a major issue in the UK (e.g. temperature effects on milk production). Where actions are in place (e.g. to improve soil health) it can be difficult to quantify the extent and impact of existing adaptation.
- For peatlands the area of restored peatland is less than the area moving to unfavourable condition annually, and this is of concern.
- In managed woodlands the forestry sector is slow to adapt, and there are considerable time lags between changing the species mix of new plantings and the period when they become commercially viable to harvest.

- In marine & coastal, although *M. gigas* is considered naturalised on the south west coast of England at present, the level of risk posed by its potential invasion of native communities elsewhere is poorly understood.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Additional adaptation measures fall into two categories, those that can be taken in advance to reduce the risk of passing a threshold, and those that occur afterwards to manage impacts.

Actions identified in this analysis that can be taken in advance include; managing nutrient inputs to lakes and rivers, rewetting of peatlands, considering climate-relevant genotypes or altered species in new woodland plantings, and moving to continuous cover forestry. All of these actions are well known and already practiced in many places, but need scaling up significantly to manage the risks from the threshold effects identified in this report.

Actions that can be taken to manage impacts subsequently include changing crop varieties or animal breeds used in agricultural production and improving livestock housing and management, and chemical remediation and temperature management of lakes and rivers. For example, riparian shading can prevent excess warming and reduce algal blooms in rivers.

**In what scenarios are there limits to adaptation?**

A number of limits to adaptation are identified in future climate scenarios for the habitats covered in this report. These relate to two key issues:

1) the extent that adaptive actions can be effective for habitats already impacted by climate change and compounding factors. For example, very degraded peatland will not re-wet; and
2) the degree of reliance on voluntary actions to achieve adaptation uptake and the temporal and spatial scale for action required.

The issue of effectiveness and cost-effectiveness is important for prioritisation of action and allocation of public funds. In this analysis, we provide evidence of risk at a habitat level with some spatial analysis but the urgency scoring for adaptation is generic and more detailed analysis is needed to assess priorities for adaption actions at a site level according to likely response, costs and benefits. For example, in some lakes or rivers it may not be feasible to control nutrient inputs. If this is the case, there may be little value in implementing adaptation options such as shading, or other restoration measures. Conversely, action to restore peatlands is a crucial tool in meeting Net Zero targets for 2050 as well as adaptation, and has been shown to be cost effective for upland peat in particular.

Where action is both necessary and justified (as above), a mix of policy tools should be considered in designing government interventions. For example, setting an appropriate regulatory baseline and implementing activities to boost awareness among landowners and managers, supported by advice and grants (as appropriate). In some instances, where land is very vulnerable to climate change, including extreme weather events, land use change may be needed. In managed woodlands, the long lead-in for adaptation to be effective, provides a greater challenge, while in marine habitats, adaptive actions may need to be undertaken at an international scale.

*Table ES1.* ***Thresholds and summary of impacts covered in national screening assessment, for baseline and under 2 °C and 4 °C scenarios (independent of time).*** *Monetary figures refer to cost of annual impacts for the UK in 2018 prices unless otherwise stated. Grey cells denote non-monetary assessment, see notes below table. Risk descriptors are listed in Appendix 2.*

| **Broad Habitat** | **Risk descriptor** | **Climate hazard** | **Societal end-point** | **Threshold** | **Mechanism** | **Impact** | **Current** | **2 °C** | **4 °C** |
|---|---|---|---|---|---|---|---|---|---|
| Freshwaters | Ne 13 | Temperature | Algal blooms (lakes) | 17 °C (lake water) | Phytoplankton growth | ↓ recreation including fishing, biodiversity; ↑ water treatment costs | £173m | £295m | £481m |
| Freshwaters | Ne 13 | Temperature | Algal blooms (rivers) | 17 °C (river water) | Phytoplankton growth | ↓ recreation including fishing, biodiversity | 0.5 | 0.9 | 2.0 [#1] |
| Freshwaters | Ne 13 | Temperature | Fish habitat | 18 °C (lake water) | Change in dissolved oxygen | ↓ biodiversity, recreational fishing | 0.9 | 1.4 | 2.5 [#1] |
| Freshwaters | Ne 13 | Temperature | Biodiversity | 14 °C (lake water) | Zooplankton composition | ↓ biodiversity | 3.2 | 3.7 | 4.9 [#1] |
| Farmland | Ne 8 | Temperature | Lamb | 9 °C (daily mean) | Parasite (*Haemonchus contortus*) | ↓ growth;↑ costs | £81m | £97m | £113m |
| Farmland | Ne 7 | Temperature | Milk | THI 74 (= 23 °C) | Heat stress | ↓ milk yield | £2.5m | £3.8m | £15.9m |
| Farmland | Ne 7 | Temperature | Wheat | 32 °C / 35 °C | Floret fertility / grain filling | ↓ wheat yield | £0m | £0m | £42m |
| Farmland | Ne 5, Ne 7 | Rainfall | Soil erosion | 30 mm (daily rainfall) | Soil loss | ↓ soil fertility; ↓ crop yield; ↓ water quality; ↓ soil biodiversity; ↓ soil carbon | £2.6m | £8.1m | £6.5m |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Peatlands | Ne 1, Ne 5, Ne 6 | Temperature | GHG emissions | 14.5 °C (warmest month) | Outwith climate envelope | ↑ GHG emissions; ↓ peatland condition, biodiversity, water quality | 3.5m $tCO_2e$; £239m | 3.6m $tCO_2e$; £318m | 4.0m $tCO_2e$; £1,319m |
| Woodlands | Ne 7 | Temperature, Rainfall | Timber (oak, other broadleaved, conifer) | 200 - 300 mm (climatic moisture deficit) | Summer drought affects tree growth & causes cracking (shake) | ↓ timber yield; ↓ wood quality | - | Species-specific risk | - |
| Coastal | Ne 17 | Temperature | Cod | 12 °C (sea bottom temperature) | Reproductive success | Δ distribution; ↓ landings | - | Range shift | Range shift #2 |
| Coastal | Ne 17, Ne 18, Ne 19 | Temperature | Pacific oyster | 825 days > 10.5 °C (sea bottom temperature) | Exceeds spawning temperature | Δ distribution; ↓ & ↑ impacts | 47 | 103 | 205 #3 |

#1 Number of months exceeding the threshold

#2 Range shift northwards

#3 Viable area for Pacific oyster reproduction (‘000 $km^2$)

*Table ES2.* ***Thresholds and summary of impacts covered in <u>case studies,</u> for CMIP5 (global climate model ensemble) and PPE (UK Met Office model) projections under RCP8.5 pathway.*** *Monetary figures refer to cost of annual impacts for the UK in 2018 prices unless otherwise stated. Woodland economic assessment not conducted. Risk descriptors are listed in Appendix 2.*

| | | | | | | **CMIP5** | | | **PPE** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Broad Habitat** | **Risk descri-ptor** | **Climate pressure** | **Societal end-point** | **Threshold** | **Impact** | **Baseline** | **2050s** | **2080s** | **Baseline** | **2050s** | **2080s** |
| Freshwaters | Ne 13 | Temperature | Algal blooms (lakes) | 17 °C (lake water) | ↓ recreation including fishing, biodiversity; ↑ water treatment costs | £173m | £263m | £332m | £173m | £329m | £420m |
| Farmland | Ne 7 | Temperature | Milk | THI 74 (= 23 °C) | ↓ milk yield | £3.1m | £8.1m | £17.0m | £4.6m | £18.4m | £57.9m |
| Peatlands | Ne 1, Ne 5, Ne 6 | Temperature | GHG emissions | 14.5 °C (warmest month) | ↑ GHG emissions; ↓ peatland condition | 3.5m $tCO_2e$; £210m | 4.9m $tCO_2e$; £1,286m | 5.1m $tCO_2e$; £1,774m | 3.5m $tCO_2e$; £210m | 5.1m $tCO_2e$; £1,344m | 7.2m $tCO_2e$; £2,473m |
| Coastal | Ne 17, Ne 18, Ne 19 | Temperature | Pacific oyster | 825 days > 10.5 °C (sea bottom temperature) | Δ distribution | 47 | 103 | 205 [#1] | - | - | - |

#1 Viable area for Pacific oyster spawning and reproduction; climate scenario from CMIP5 projections

*Table ES3.* ***Thresholds and risk of irreversible change***

| CCRA3 Risk descriptor | Habitat | Climate pressure | Societal end-point | Risk of irreversible change | CCRA3 Adaptation response |
|---|---|---|---|---|---|
| Ne 13 | Freshwaters | Temperature | Algal blooms (lakes) | Medium-term, difficult to reverse | More action needed |
| Ne 13 | Freshwaters | Temperature | Algal blooms (rivers) | Medium-term, difficult to reverse | More action needed |
| Ne 13 | Freshwaters | Temperature | Fish habitat | Long-term, effectively irreversible | More action needed |
| Ne 13 | Freshwaters | Temperature | Biodiversity | Long-term, effectively irreversible | Further investigation |
| Ne 8 | Farmland | Temperature | Lamb | Long-term, effectively irreversible | Further investigation |
| Ne 7 | Farmland | Temperature | Milk | Short lived, reversible | More action needed |
| Ne 7 | Farmland | Temperature | Wheat | Year-long, reversible | Further investigation |
| Ne 5, Ne 7 | Farmland | Rainfall | Soil erosion | Long-term, effectively irreversible | More action needed |
| Ne 1, Ne 5, Ne 6 | Peatlands | Temperature | GHG emissions | Long-term, effectively irreversible | More action needed |
| Ne 7 | Woodlands | Temperature, Rainfall | Timber (oak, other broadleaved, conifer) | Long-term, effectively irreversible | More action needed |
| Ne 17 | Coastal | Temperature | Cod | Long-term, effectively irreversible | Sustain current action |
| Ne 17, Ne 18, Ne 19 | Coastal | Temperature | Pacific oyster | Long-term, effectively irreversible | Further investigation |

# Contents

# 1 Introduction

To inform the ASC's Evidence Report for the third UK CCRA, the Adaptation Committee has commissioned a range of research projects that aim to improve the evidence supporting, and impact of, the CCRA. This project aims to produce new research on climate-driven threshold effects within the natural environment, and the role of adaptation (natural and human responses) in moderating the threshold effects.

Current approaches and models to predict future climate change impacts are often based on simple linear projections of climate variables, and ecological responses. These are assumed to be either linear or monotonic (i.e. non-linear but unidirectional and predictable, e.g. exponential functions describing responses to rising temperatures). In reality, natural ecosystems are subject to multiple interacting pressures, operating on a range of timescales, and may respond unpredictably to the accumulation of these pressures, and to the superimposed effects of an extreme event. For example, a catastrophic wildfire may result from a combination of long-term land-use (drainage, accumulation of woody biomass), long-term changes in climate (warming, drying) and stochastic events (drought, deliberate or accidental fire-setting). Similarly, saltwater inundation of agricultural land may be a consequence of past land reclamation, drainage-induced subsidence, long-term sea-level rise and a storm-surge. Impacts of threshold crossing can be complex. For example, in woodland, the evidence of climate driven disturbance dynamics shows complex interactions and feedbacks (Seidl et al. 2017), and there is evidence that climate driven forest disturbances are cancelling out production benefits in European forests (Reyer et al, 2017).

The combined impact of multiple cumulative pressures and acute 'trigger' events is inherently difficult to predict, yet it is of fundamental importance in projecting and adapting to the impacts of future climate change. In particular, it may lead to threshold-type responses, leading to rapid change in ecosystems, often resulting in undesirable impacts on society.

In CCRA2, the Adaptation Committee (AC) took a three-step approach to assess the urgency of additional action for each climate risk and opportunity, namely:

1) considering the magnitude of the risk now and in the future
2) taking into account policies and adaptation plans already in place to manage the risks, and
3) considering the potential benefits of further action

Crossing of thresholds can, at worst, result in irreversible changes to the natural environment, loss of natural capital, impairment of ecosystem functions and services, and negative consequences for human well-being. Through identifying and analysing the effect of crossing such thresholds, and prioritising those which have the most impact on society, this project will help better assess the nature of the risk (step 1 in the urgency method) the effectiveness of current adaptation strategies to manage the risks (step 2 in the urgency method), and what the effects of further potential adaptations might be (step 3 in the urgency method). In many cases, this kind of assessment can only be realistically run by using integrated calculation chains, which take into account change in the climate driver, associated factors which contribute to sensitivity of the ecosystem to perturbation, impacts on the ecosystem, and subsequent impacts on ecosystem services, or the benefits provided to humans by the environment.

Recent work in the economics of climate change has highlighted the large potential economic costs associated with crossing certain ecosystem thresholds (Diaz and Keller, 2016; Convery and Wagner, 2015). Understanding the possibility of crossing these thresholds and quantifying the costs associated with them could substantially alter the overall costs to the UK from climatic changes and create an additional domestic case for mitigating greenhouse gases. Indeed, failure to account for non-linear interactions between the climate, natural environment and the economy risks overlooking potentially irreversible and costly events. Many of these effects are not accounted for in conventional models of climate change impacts.

In addition, assessing which adaptation measures represent feasible means of avoiding crossing thresholds is a crucial aspect for the CCC in developing recommendations for prioritising certain measures and the timeframes within which adaptations can be most effectively employed (Benton et al., 2017). Quantifying these effects both in terms of their expected physical magnitude and their economic value is an important step in creating a basis to make timely and efficient investments to ensure environmental and economic sustainability in the UK in the medium and long term. There is a need to clearly set out the state of evidence on the possible effects of crossing these thresholds in the natural environment, what is understood about the magnitude of their impacts, and what future action and research needs to take place. This is an important next step to inform government, business, and the public about future environmental and economic priorities.

The CCRA2 Evidence Report notes that 'effective adaptation cannot be undertaken without careful consideration of the cross-cutting nature of risks and synergies between adaptation activities'. This is of particular relevance in the natural environment where changes in land use and management resulting from climate change, or as an adaptation to climate change for a given ecosystem service, can support or undermine the delivery of other ecosystem services and indeed other sectors. For this reason, the assessment of risks, thresholds and adaptation actions in this project will ensure that the cross-cutting nature of risks and synergies is addressed throughout.

# 2 Aims and objectives

The aims of this project are to:

- provide improved evidence of possible climate risks in the natural environment that do not follow linear patterns of change;
- assess the resulting impacts of these effects on different areas of society (e.g. communities, industries, workforces);
- identify what aspects of society are most at risk; and
- assess the extent to which current and potential future adaptation strategies can address the risk, either through preventing the threshold impact from occurring or managing the impact when it does.

Specifically, the project sets out to answer six questions:

1. What climate hazard thresholds represent points beyond which the effective functioning of key systems within the natural environment may be compromised, and why?
2. What are the resulting impacts on the goods and services provided to society from the natural environment? What would be the quantified impact?
3. Is there a risk of irreversible change in the ecosystems affected, or substantial time lags in recovery?
4. What is the impact of current levels of adaptation at mitigating these risks?
5. What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?
6. In what scenarios are there limits to adaptation?

# 3 Overview of thresholds and their application in this study

## 3.1 Threshold definition used

In this study we define a threshold as "the point at which a non-linear change in an ecosystem component or property occurs as a result of change in a climate driver". This draws on definitions in Andersen et al. (2009) and Scheffer (2009). The threshold itself is the value for the climate variable beyond which impacts become non-linear. The impacts of crossing the threshold are defined more widely. In order to satisfy the required emphasis on the goods and services provided by ecosystems, and acknowledging the highly inter-connected role of people in social-ecological systems, the definition of impact includes non-linear changes in ecosystem services or on society as well as impacts on biodiversity and ecosystem function *per se*.

This definition of a threshold does not restrict the analysis to strict interpretations of tipping points as only applying to irreversible change, or situations which demonstrate significant hysteresis. The threshold impacts assessed range from physiological effects on individual species, like the spawning of Pacific Oyster (*Magellana gigas*) or declines in milk production of dairy cows, to impacts on community-level changes in species composition (e.g. zooplankton communities in lakes), or the habitat condition of blanket bog.

There is increasing evidence that it is acute climate events (extremes) rather than chronic i.e. slow steady average change in climate conditions which lead to non-linear effects in ecosystems (Turner et al. 2020). This causes difficulties in assessing future risk for a number of reasons. Firstly, the climate models are better at predicting steady change in climate variables than they are at predicting extremes. Secondly, there are inherent difficulties in estimating ecosystem responses to extremes, because the resilience of the ecosystem needs to be taken into account, as well as the frequency and the magnitude of the extremes experienced. As an example, peat bog vegetation can recover from a severe drought or a fire as long as it is not suffering from excessive pressure from other factors such as grazing or alteration to the natural hydrological regime. However, even a peat bog in good condition is unlikely to be able to withstand frequent droughts or fires. Since frequent extreme events do not occur at the moment, and are difficult to replicate at scale experimentally, there is very little evidence on which to base an assessment of these impacts.

Some of the thresholds assessed in this study incorporate the likelihood of extreme events implicitly, by having longer time frames embedded within the threshold metric itself, or by calculating the number of years in a ten-year period for which the threshold is exceeded. For example, peatlands use a climate envelope based on a 30-year climate mean, while the spawning of Pacific oyster calculates a frequency of spawning in a ten year period. However, not all of the thresholds do so.

The impact of crossing a threshold can be temporary, such as declines in milk production which recover over periods of days, to longer term or (near) irreversible, such as species extinction. Thresholds linked to policy targets were not considered relevant, i.e. if the ecological status of a water body shifts from the class ‘Good status’ to the class ‘Moderate status’ in the EU Water Framework Directive, that was not considered as crossing a threshold.

The nature of the thresholds vary, therefore the analysis approach has to be tailored to each individual assessment. In some cases, additional processing is required to calculate the equivalent threshold in a climate variable available from climate models, from the underlying driver which causes non-linear change in an ecosystem. For example, the physiological threshold temperature for Pacific Oyster spawning is based on sea bottom temperatures, requiring a conversion from sea surface temperatures to sea bottom temperatures. In some analyses, this step is achieved within established models, in other cases, such as the conversion from air temperature to lake water temperature for impacts on a number of freshwater ecosystems, additional data was sourced to underpin the calculation.

The following schematic (Figure 1) illustrates how a simple temperature threshold is applied. The lower panel shows how temperature increases linearly with time. At the point where an ecological threshold is reached, some form of ecological impact occurs, represented in the top panel. Two simple examples are shown, in R1 the impact increases in proportion to the rise in temperature above the threshold, while in R2 the relationship is curvi-linear and the impact increases at a greater rate. At a given point in time, depending on where the threshold lies, and due to climatic variation across the UK, some or all of the regions in the UK may lie below or above, or may span the threshold. This variation is represented by the blue box. Note that due to inter-annual variability in climate parameters, a threshold based on a climate variable may be exceeded in some years and not others.

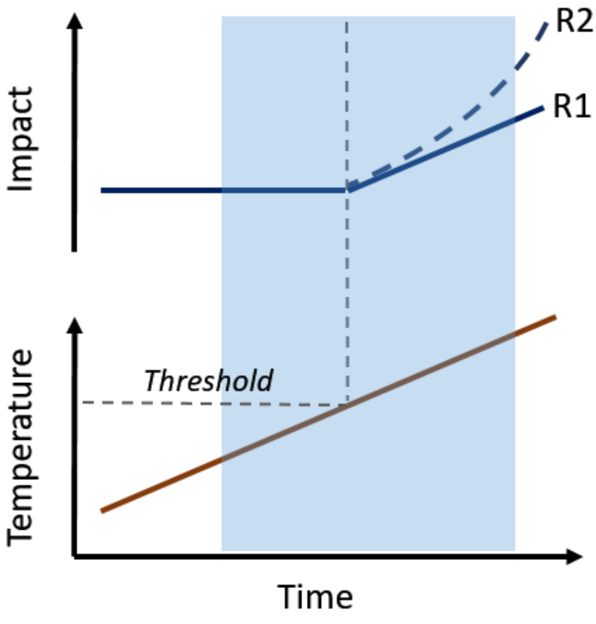


*Figure 1.* ***Schematic illustrating impacts above a temperature threshold.***

# 4 Methods – Overview

This section provides a brief summary of the methods used in the analysis. For each assessment conducted on a potential impact, specific methods are provided in the write up for both the national screening and the case studies. Where additional detail is needed, this is provided in Appendix 1.

## 4.1 Habitat / ecosystem definitions

The assessment was separated across the following ecosystem types to ensure balance across a range of end-points, and to structure the evidence gathering at the initial review phase. These ecosystem types broadly follow the UK National Ecosystem Assessment (Watson et al. 2011) definitions of Broad Habitats, summarised in Table 1 below. These definitions were used to conduct the initial literature reviews. Subsequent assessments focused on more tightly defined categories within a Broad Habitat type, which were the focus of the threshold impacts taken forward for assessment.

*Table 1. **Ecosystem categories used in this assessment, broadly corresponding to UKNEA Broad Habitats**.*

| Ecosystem type | NEA Broad Habitat | Definition |
|---|---|---|
| Freshwaters | Freshwaters and wetlands | Lakes, rivers and streams, wetlands |
| Farmland and grassland | Enclosed farmland, Semi-natural Grasslands | Arable land and pasture, including intensive and extensive grazing systems |
| Mountain moors and heaths | Mountain, moors and heaths | All peatlands |
| Woodlands | Woodlands | All woodlands |
| Marine and coastal margins | Marine and coastal margins | Marine and coastal margin habitats |

## 4.2 Impact chains

Impact diagrams were constructed following a template (Figure 2) which includes the climate driver, threshold, natural capital asset, ecosystem processes, functions or attributes, and endpoints which reflect societal interest. These endpoints include the ecosystem services they provide, the social or economic impacts and biodiversity. Current and potential adaptation options are included, with arrows showing which parts of the chain it is possible to manage through adaptation. Some impacts are dependent on, or are influenced by, key predisposing factors. These may be physical factors such as soil type, or may be linked to management of the ecosystem or its surroundings, such as input of elevated nutrient levels to lakes. Only the most important pre-disposing factors are identified in these chains. In reality, multiple interacting factors govern the sensitivity to climate impacts for ecosystems (Turner et al. 2020). In some chains, a sequence of impacts occurs in the ecosystem before there is an impact on a societal end-point, represented in this diagram as function 1, function 2 etc. For example, in farmland heavy rainfall leads to soil erosion, which in turn leads to reduced soil fertility, causing lower crop yields.

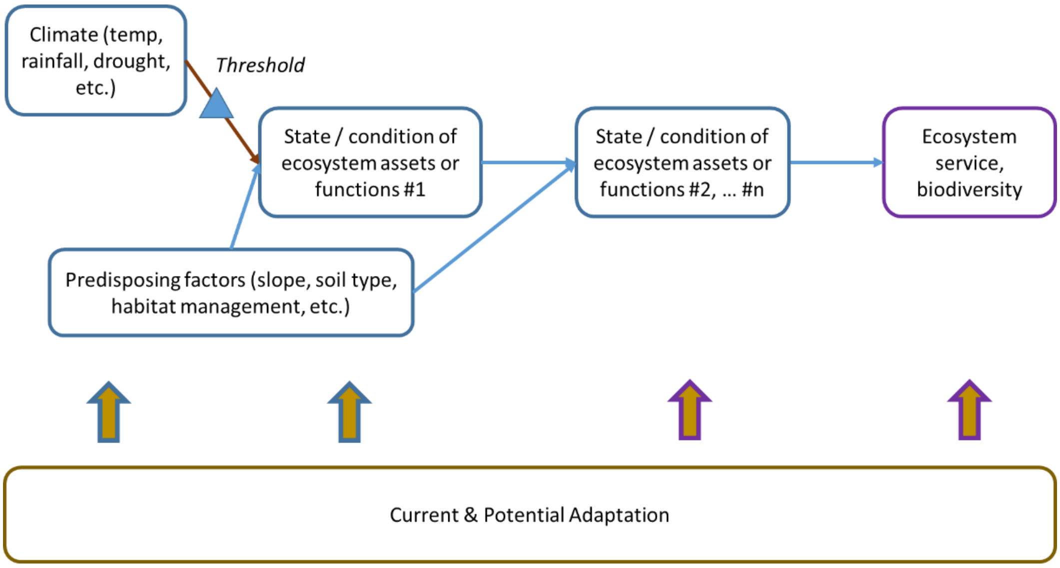


*Figure 2.* ***General schema for impact chains.***

## 4.3 Stages in the assessment

Following the project structure, the work was undertaken in three main phases. 1) A review of the evidence to identify thresholds, 2) A rapid assessment at national level to quantify selected impacts, and 3) More detailed case study assessments of a subset of impacts. This process is summarised in Figure 3. At each phase, the objectives of this report were considered. In particular, the assessment considered adaptation options for each impact.

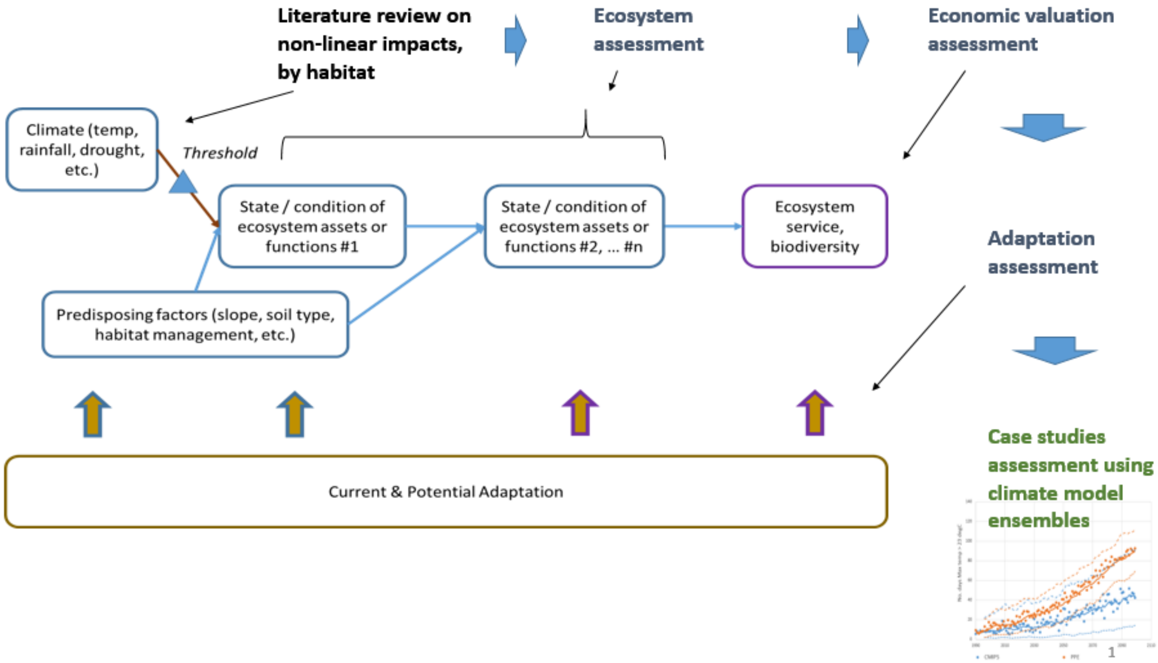


*Figure 3.* **Schema showing the three stages of the assessment**. *In annotated comments clockwise from top left: Black text shows stage 1, blue text denotes stage 2, green text denotes stage 3.*

**Phase 1. Literature review:** Rapid evidence reviews of the literature were conducted to assess whether thresholds had been identified in the literature for each Broad Habitat type. The reviews evaluated both published and grey literature in a structured way, described in Appendix 1 for each Broad Habitat. The selected studies were supplemented after discussion with experts outside of the search team to ensure key studies were not missed. The list of thresholds were scored according to their importance (1 = Clear biophysical or societal threshold, quantified; 2 = Clear biophysical or societal threshold, but not quantified; 3 = Possible biophysical or societal threshold, uncertain but with high potential impact; 4 = Threshold effects unclear, or low potential impact). Those identified impacts which scored 1, 2 or 3 were taken forward to the rapid assessment phase.

**Phase 2. National screening assessment:** The aim of the screening exercise was to conduct a rapid assessment of as many of the potential threshold impacts as possible, in order to obtain an overview of which impacts were more important, and their geographical scope. For each threshold, an impact chain was created (see Figure 2 above), and the impacts were quantified as far as possible towards the end of the chain. The assessment was national in scope, but separately calculated impacts at regional level. Results were calculated for each climate area of the UK, using CCRA3 defined regions (Figure 4), broadly equivalent to NUTS2 level regions. As this was a rapid assessment, the analysis used climate data from a single model projection (HADGEM PPE model id 7 – see section 4.4), selected as one following a pathway roughly in the middle of the range of ensemble members, from Lowe et al. (2018). The assessment focused on the points at which the ensemble member reached 2 °C, and 4 °C. In the national screening assessment, these are termed 2 °C and 4 °C scenarios respectively (see section 4.4). With the requirement to conduct as many assessments as possible, right through to valuation, it was not possible to incorporate the full complexity of factors influencing threshold exceedance including the many potential interacting variables which also affect sensitivity to climate drivers. In some assessments, the analysis approach we have taken incorporates many of these factors implicitly into the calculations. For example, the economic costs associated with algal blooms in lakes incorporates levels of adaptation and observed eutrophication at baseline in the estimates. Soil erosion risk takes into account geographical variation at fine scale in erosion risk across the UK and scales future risk due to rainfall accordingly. In other assessments, the calculations were simplified to the main impact pathway where it was not possible to incorporate other contextual information.

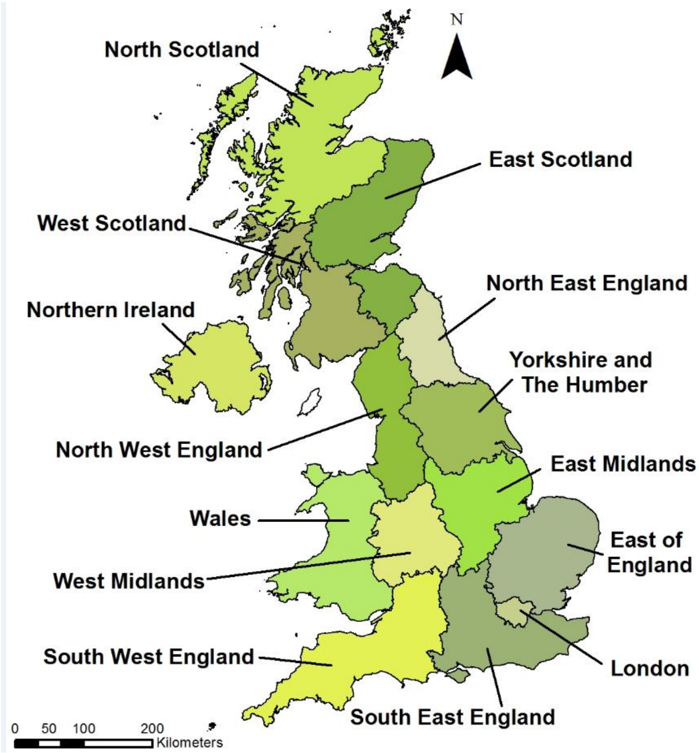


*Figure 4.* ***Defined regions of the UK used for calculation of regional variation in national screening and case study assessments (Met Office Hadley Centre, 2018).***

**Phase 3. Case study analysis:** One impact from each Broad Habitat was selected as a case study for more detailed analysis. These were selected primarily on the basis of greater economic impact, and/or on robustness of the underpinning evidence available for the assessment. The principle focus for these more detailed analyses was improved representation of the range of variability in the climate data. However, for some impacts, the analysis method was also adapted. The climate data for the majority of these analyses used all 28 projections from across the two families of ensembles available from UKCP18 data at the time of analysis, PPE and CMIP5. The one exception was woodland, which excluded one model ensemble member which did not have rainfall data at the time of analysis. The data used is described in more detail in section 4.5. The case study assessments focused on the trajectory towards a 4 °C world under a RCP8.5 concentrations pathway, looking at impacts during baseline and at two time-points along that trajectory, the 2050s and the 2080s. Data for the trajectory towards a 2 °C world was not available at the spatial or temporal resolution required for the majority of these analyses, at the time this assessment was conducted.

## 4.4 Climate data – screening assessment

Climate data to run the national screening assessments were extracted from UKCP18 12 km projections for a RCP8.5 concentrations pathway. A single ensemble member was selected, roughly mid-range of the set of ensembles (Lowe et al. 2018). The ensemble member used was the HADGEM3 Perturbed Physics Ensemble Model ID 7. Climate data were extracted for 10-year time-slices for the following time periods:

- Baseline (2001-2010)
- 2 °C scenario (2025-2034), centred on 2031, the year in which PPE model i.d. 7 hits 2 °C
- 4 °C scenario (2060-2069), centred on 2064, the year in which PPE model i.d. 7 hits 4 °C

For some assessments, the baseline period was adjusted in order to match available ecosystem impact or economic assessment data. The climate data used in the assessments differed for two habitats: Marine and coastal – see section 16.5 for details; for woodlands – see section 8.3 for details.

## 4.5 Climate data – case studies

Climate data to run the case study assessments were extracted from UKCP18 60 km projections for a RCP8.5 concentrations pathway. Two sets of projections were used: one set of 15 projections from the new Met Office Hadley Centre climate model (HadGEM3-GC3.05) produced by generating a perturbed parameter ensemble (PPE), and a set of 13 projections from models that informed the IPCC 5th assessment (CMIP5). Data from all 28 projections were extracted and used in each analyses where possible. For each impact, results were analysed separately for the PPE ensemble and the CMIP5 ensemble. The marine and coastal assessments on cod and Pacific oyster used a different approach to calculate sea surface temperatures – see section 16.5 for details. The case study analysis compared the following time periods, unless specified otherwise:

- Baseline (2000-2019)
- 2050s (2040-2059)
- 2080s (2070-2089)

## 4.6 Economic assessment methodology

The economic assessment conducted throughout this study quantifies the magnitude of changes in the provision of ecosystem services where thresholds have been identified in monetary terms. The economic assessment uses data derived directly from the ecosystem service assessment, which quantifies annual physical changes in ecosystem services under current and future climate scenarios. Accordingly, economic impacts are expressed in annual terms in order to compare the magnitude of economic impacts under current climatic condition with future conditions. The 2018 price level is used throughout the report unless otherwise stated.

Throughout this study, we use a variety of market and non-market valuation methods to assess the magnitude of impacts on ecosystem services in monetary terms. Market impacts refer to goods or services traded on markets, such as agricultural products. Non-market goods and services are not generally priced and require economic valuation techniques that use alternative methods to estimate the value to society. Examples of non-market impacts in this study are the value of greenhouse gas emissions from peatlands or lost amenity values and water treatment costs from algal blooms in freshwaters. The methodology used to value each ecosystem services is detailed in each section of the report.

The ecological and economic assessments were conducted for the screening assessment and the case studies as visualised in Figure 5. The annual cost was calculated for the baseline period, and for two subsequent scenarios (screening assessment) or time periods along a climate trajectory (case studies) - see the methods sections above for the climate data for more detail.

This study does not aim to estimate the difference between economic impacts under linear versus threshold behaviour. Instead, it aims to show the time course of impacts as they are projected to develop under future climate trajectories, and to quantify those impacts under specified future conditions or time points, assuming that current adaptation is held constant. This approach was taken in order to identify shortfalls in adaptation and, using the case studies, to show the likely timelines of impact. For the same reason, other factors which increase the susceptibility of ecosystems to non-linear change (such as eutrophication combined with increasing water temperature for algal bloom development) were also held constant. In reality, many of the associated preconditions or contributing factors will also alter with climate change. Modelling such aspects requires dynamic models, and was beyond the scope of this project. Non-linear change in one ecosystem function or service may induce changes in others. Some of these interacting risks are explored in a separate research project supporting CCRA3.

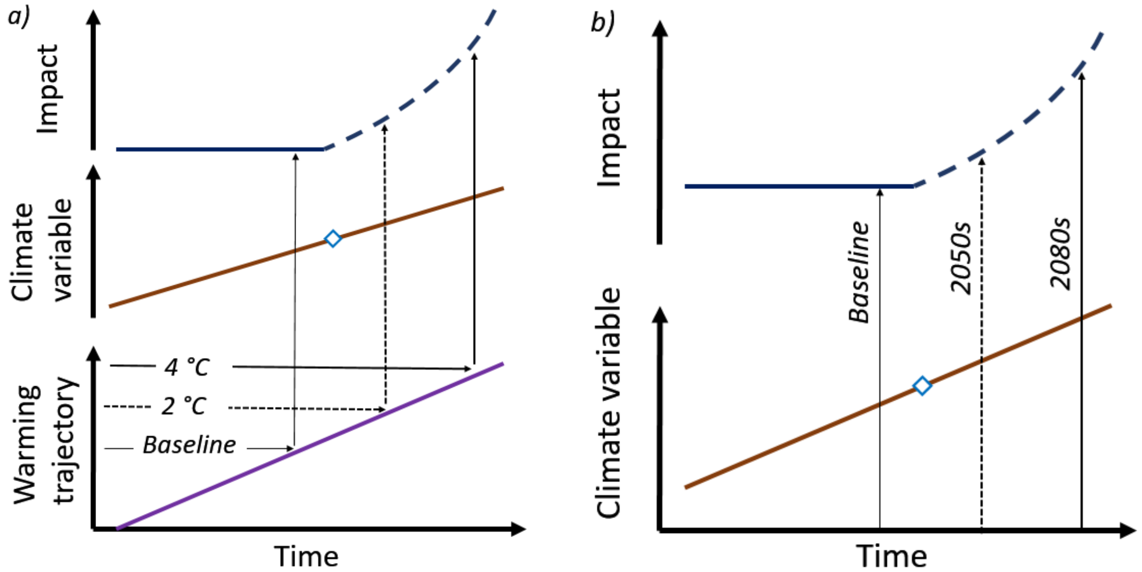


*Figure 5. **Schematic illustrating how ecological and economic assessments were carried out**. Showing a) scenarios in the screening assessment, and b) time periods in the case studies. For illustration, a notional example threshold is shown, where baseline is below the threshold and subsequent impacts occur above the threshold.*

## 4.7 Adaptation assessment methodology

Evidence on current adaptation measures and their efficacy was based on a search of the literature. Actions outlined in the Government's National Adaptation Programme (NAP) have been listed for each habitat assessment to provide information on current status and plans. This involved extracting information from the second NAP as well as Appendix A, 'National Adaptation Programme action updates'[1], of the CCC 2019 Progress Report to Parliament. However, in many cases evidence on more adaptive actions for future climate scenarios was lacking. Relevant evidence from other climates has been used where no UK specific examples were available.

The framework from CCRA3 internal workshops was used as a template for presenting the adaptation evidence, which includes sections on:

[1] https://www.theccc.org.uk/wp-content/uploads/2019/07/Appendix-A-NAP-action-updates-2019.xlsx

- Nature of adaptation;
- Current status and plans;
- Benefits of adaptation since 2012;
- Potential further action or investigation;
- Case for action in the next 5 years;
- Whether risk is managed by autonomous or planned adaptation;
- Risks of lock-in;
- Risk(s) interacting; and
- Urgency scoring.

The urgency scores are based on the urgency categories used in the UK Climate Change Risk Assessment 2017 Evidence Report. These classifications are:

- More urgent – More action needed: *New, stronger or different government policies or implementation activities – over and above those already planned – are needed in the next five years to reduce long-term vulnerability to climate change.*
- More urgent – Research priority: *Research is needed to fill significant evidence gaps or reduce the uncertainty in the current level of understanding in order to assess the need to additional action.*
- Less urgent – Sustain current action: *Current or planned levels of activity are appropriate, but continued implementation of these policies or plans is needed to ensure that the risk continues to be managed in the future. This includes any existing plans to increase or change the current level of activity.*
- Less urgent – Watching brief: *The evidence in these areas should be kept under review, with long-term monitoring of risk levels and adaptation activity so that further action can be taken if necessary.*

For each threshold, three key questions are asked:

- What is the impact of current levels of adaptation at mitigating these risks?
- What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts? and
- In what scenarios are there limits to adaptation?

The text around limits to adaptation considers physical and ecological, technological, informational, social, and financial barriers.

## Literature review

The rapid evidence reviews identified 37 thresholds in the literature with relevance to UK habitats. The full list of identified thresholds are provided in Appendix 1, by habitat. The scoring exercise led to a selection of 12 thresholds across the five broad habitats where enough evidence was available to undertake some form of national screening assessment, and impacts were assessed as of high magnitude or importance against the criteria described in the methods for Phase 1 above.

Note that this structured approach, focusing primarily on published and grey literature studies by habitat, does not represent an exhaustive list of all possible threshold-based impacts. It should also be recognised that some impacts identified in the literature review could not be quantified because of a lack of data, lack of a specified threshold, or insufficient evidence on which to base an assessment. Two examples illustrate the difficulty of this task. Roy et al. (2017) aimed to conduct a horizon scanning exercise for potential pathogen and invasive alien species impacts on biodiversity, but concluded that substantial knowledge gaps hindered such an exercise. Meanwhile, in marine systems which contain some of the classic examples of regime shifts, Spencer et al. (2011) used a data-driven approach to detect regime shifts in UK marine ecosystems from long time-series data, covering five organism groups (fish, infaunal benthos, marine benthos, plankton & rocky shore invertebrates) from seven marine regions of the UK. From their analysis, they concluded that UK marine communities may be dominated by gradual trends rather than sudden shifts. Some impacts were not taken forward for assessment due to lack of time within the project. The main impact falling into this category was temperature effects on salmonid fish in rivers.

# National Screening Assessment of threshold-based impacts, by NEA broad habitat

## 5 Freshwater

### 5.1 Summary - Freshwater

The literature review assessed impacts on all Freshwaters including lakes, rivers and wetlands (but excluding bogs and fens, which are covered under peatlands). This identified 18 potential impacts (section 16.1.1), of which four were taken forward for the national screening assessment. All four were linked to temperature: algal blooms in lakes, algal blooms in rivers and streams, volume of thermally-suitable fish habitat in lakes and zooplankton composition in lakes. Temperature effects on salmonids are recognised as an important impact, but could not be assessed in this study due to time limitations. A case study focused on one impact in more detail: algal blooms in lakes.

Many of the impacts on freshwaters have a similar underlying mechanism, i.e. temperature impacts on plankton composition, mediated by nutrients, although the temperature thresholds at which these occur differ between systems. For example HABs form in lakes above 17 °C and lowland rivers above 19 °C. As a consequence, many of the adaptation options are similar and centre on nutrient management, but again there are variations in the most effective adaptation measures between the impacts due to habitat-specific and impact-specific factors.

*Temperature effects on algal blooms in lakes (Risk descriptor: Ne 13)*

Where mean monthly water temperature exceeds a 17 °C threshold, in combination with elevated nutrients (primarily phosphorus), there is increased incidence of algal bloom formation in lakes. This leads to reduced water quality and negative impacts on a range of services including drinking water production, recreation and biodiversity.

The overall ecological risk under a 4 °C scenario is projected to be low in Wales, medium in Scotland and high in England and Northern Ireland. At a UK level, the costs of algal blooms are projected to increase from £173 million at baseline to £295 million under a 2 °C scenario and £481 million under a 4 °C scenario.

Current adaptation measures focus on catchment-wide management of nitrogen and phosphorus, applied in nitrate vulnerable zones, but not widely elsewhere. The contribution from waste water discharge is also significant and should be managed through regulation and water company planning. Chemical remediation has been trialled in a limited number of severely affected water bodies, but not widely. Therefore the impact of current levels of adaptation on mitigating these risks is low.

**Urgency scoring -** More urgent: more action needed – Capacity is available to reduce nutrient loading and benefits from early action will be seen within the next five years. Further research may be required for some measures which are not currently widely practiced (internal loading control, aeration, artificial mixing, and shading).

*Temperature effects on algal blooms in rivers (Risk descriptor: Ne 13)*

Above a monthly mean water temperature of 19 °C, and in combination with elevated nutrient levels, there is an increased risk of algal blooms developing in lowland rivers. This leads to a decrease in water quality, and impacts on the ecosystem services that depend on good water quality, including recreation.

The overall ecological risk under a 4 °C scenario is projected to be low in Scotland, medium in Wales and Northern Ireland and high in England. No economic assessment was conducted for this service.

Current adaptation measures focus on catchment-wide management of nitrogen and phosphorus, applied in nitrate vulnerable zones, but not widely elsewhere. The contribution from waste water discharge is also significant and should be managed through regulation and water company planning. Other management aspects such as riparian planting to shade river channels have received relatively little focus so far. Therefore the impact of current levels of adaptation on mitigating these risks is low.

**Urgency scoring -** More urgent: more action needed – Capacity is available to reduce excess nutrient loading, and benefits from implementing this adaptation will be seen within the next five years.

*Temperature effects on fish habitat volume in lakes (Risk descriptor: Ne 13)*

Above a threshold mean monthly lake water temperature of 18 °C, increased phytoplankton and lower dissolved oxygen lead to a decrease in the thermally suitable habitat for rare fish species such as the vendace. We are already close to extinction of this species in the UK, which would result in biodiversity loss and a loss in the ecosystem services these fish provide, including recreational fishing.

Vendace only occurs in two UK regions, west Scotland and north west England. The ecological risk under a 4 °C scenario is projected to be medium in Scotland and high in England. This may lead to extinction of this species in the UK. No economic assessment was conducted for this service since the conservation value of this species is not well understood.

Current adaptation measures focusing on catchment-wide management of nitrogen, phosphorus and suspended sediment (including waste water discharge), or reduction in internal nutrient cycling can be applied to lakes containing rare species, but are not widely applied. The provision of artificial spawning substrates may help offset the siltation of spawning grounds. Identification of new sites within their future climate range, and the translocation of eggs, larvae and adults can be used to establish refuge populations in high-quality sites. These approaches are also not widely applied and the impact of current levels of adaptation at mitigating these risks is low. However, identifying lakes that are still within thermal range for specific fish species is key as other adaptive measures will only work if the thermal regime is suitable.

**Urgency scoring -** More urgent: more action needed – Capacity is available to reduce excess nutrient loading, and benefits from implementing this adaptation will be seen within the next five years.

*Temperature effects on zooplankton composition in lakes (Risk descriptor: Ne 13)*

Above a monthly mean water temperature of 14 °C, changes in the community composition of the zooplankton community are likely to occur. Changes at this trophic level potentially cascade throughout food webs in complex ways, and therefore cannot be easily translated into impacts on ecosystem services.

The ecological risk under a 4 °C scenario is projected to be high in all UK regions, due to current day temperatures being at or above the threshold already in most areas. No economic assessment was conducted for this service since it was not possible to translate changes in zooplankton community into an associated change in ecosystem service provision.

Current adaptation measures focus on catchment-wide management of nitrogen and phosphorus, applied in nitrate vulnerable zones, but not widely elsewhere. The contribution from waste water discharge is also significant and should be managed through regulation and water company planning. Chemical remediation has been trialled in a limited number of severely affected water bodies, but not widely. Therefore the impact of current levels of adaptation at mitigating these risks is low.

**Urgency scoring -** More urgent: research priority – Capacity is available to prevent nutrient loading and benefits from early action will be seen within the next five years. Further research may be required for some measures which are not currently widely practiced (internal loading control, aeration, artificial mixing, and shading).

## 5.2 Overview: Freshwater – national screening assessment

This section covers impacts in freshwaters including lakes, rivers and wetlands within the Broad Habitat type defined in the UK National Ecosystem Assessment (UKNEA, 2011). Four out of eighteen potential threshold-based impacts were taken forward in the national screening assessment. All four thresholds were related to increasing water temperature: three of the impacts occur in lakes, with increased incidence of algal blooms, reduction in the volume of thermally-suitable fish habitat, and changes in the community composition of plankton. The fourth impact is increasing incidence of algal blooms in rivers. Table 2 summarises the climate hazard thresholds at which damage starts to occur to the natural asset and the ecosystem services it provides, and lists those main impacts. The full list of potential impacts identified in the literature review can be found in Section 16.1.

*Table 2. **Potential threshold-driven impacts in freshwaters**. Evidence for each of these thresholds is provided in the text below.*

| Climate-mediated stressor | Habitat | Threshold | Biophysical response | Societal end-point affected | Aligned risk descriptors |
|---|---|---|---|---|---|
| Temperature | Lakes | 17 °C monthly mean lake water temperature | Phytoplankton composition, biomass and blooms | Drinking water, recreation including fishing, biodiversity | Ne 13 |
| Temperature | Rivers, streams | 19 °C monthly mean water temperature of lowland rivers | Phytoplankton composition, biomass and blooms | Recreation, biodiversity | Ne 13 |
| Temperature | Lakes | 18 °C monthly mean lake water temperature | Fish habitat volume | Biodiversity, recreational fishing | Ne 13 |
| Temperature | Lakes | 14 °C monthly mean lake water temperature) | Zooplankton composition | Biodiversity | Ne 13 |

Across the UK there are approximately 42,000 lakes, and total river length is of the order of 280,000 km[2]. The distribution of these water bodies is highly variable among UK regions (Table 3), with an especially large quantity of freshwater habitat in Scotland.

[2] Based on data from UK Lakes Portal ( https://eip.ceh.ac.uk/apps/lakes/ ) and the Intelligent Rivers Network

*Table 3***. Number of lakes and total river length in UK regions.** *n.d. = No data. Data extracted from the UK Lakes Portal (https://eip.ceh.ac.uk/apps/lakes/) and the Intelligent Rivers Network. Upland and lowland rivers differentiated as reaches above or below 80 m elevation. *River length data not provided for Northern Ireland.*

| Region | No. Lakes | Upland river length (km) | Lowland river length (km) | Total river length (km) |
|---|---|---|---|---|
| North West England | 1,857 | 6,531 | 12,022 | 18,553 |
| North East England | 671 | 2,585 | 8,943 | 11,527 |
| Yorkshire and Humber | 1,593 | 8,594 | 8,823 | 17,417 |
| West Midlands | 2,071 | 5,369 | 8,507 | 13,876 |
| East Midlands | 1,649 | 11,488 | 5,090 | 16,578 |
| East of England | 2,105 | 14,143 | 1,271 | 15,413 |
| South West England | 1,878 | 11,982 | 10,537 | 22,519 |
| South East England | 2,693 | 14,255 | 3,256 | 17,511 |
| London | 275 | 932 | 40 | 973 |
| Wales | 1,391 | 7,122 | 20,099 | 27,221 |
| North Scotland | 20,289 | 11,670 | 43,445 | 55,115 |
| West Scotland | 3,242 | 7,244 | 26,632 | 33,875 |
| East Scotland | 2,085 | 5,439 | 25,945 | 31,384 |
| Northern Ireland* | 22 | n.d. | n.d. | n.d. |
| | | | | |
| England total | 14,792 | 75,879 | 58,488 | 134,368 |
| Wales total | 1,391 | 7,122 | 20,099 | 27,221 |
| Scotland total | 25,616 | 24,353 | 96,022 | 120,374 |
| Northern Ireland* total | 22 | n.d. | n.d. | n.d. |
| | | | | |
| **UK Total** | **41,821** | **107,555** | **174,948** | **282,504** |

## 5.3 Temperature effects on phytoplankton blooms in lakes

Figure 6 below summarises the threshold and assessment chain. Lake temperatures are likely to warm in line with air temperature, with associated increases in stratification of lakes. Above a water temperature of 17 °C, and in combination with elevated nutrient levels, harmful algal blooms are more likely to form, leading to a decrease in water quality and adverse effects on the range of ecosystem services which are dependent on that water quality. More detailed assessment of this impact is provided in a case study (section 10), which focuses on a wider set of climate projections.

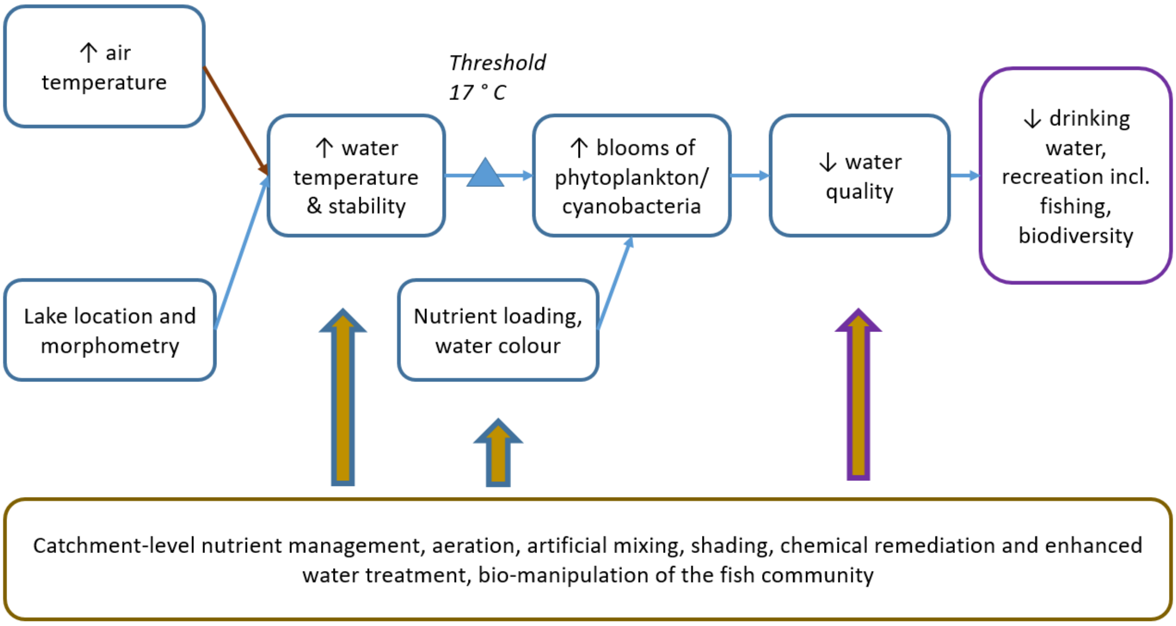


*Figure 6.* **Impact chain for temperature effects on phytoplankton blooms in lakes**. *Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures.*

### 5.3.1 Justification of threshold used in the assessment

Lake temperatures are likely to warm in line with air temperature, with associated increasing water column stability as a result of thermal stratification in lake ecosystems. Warming stimulates the growth of phytoplankton species capable of forming blooms, particularly favouring harmful algal blooms of cyanobacteria, as does the improved underwater light climate that results from increased water column stability (Paerl & Huisman 2008; Elliott *et al* 2010, 2012; Richardson et al. 2018; Ho et al. 2019). Increased availability of nutrients due to eutrophication can further enhance phytoplankton growth with rising temperatures. Changing water colour also modulates the temperature effect in different ways. It is indicative of organic inputs that can both supply additional nutrients but also limit the availability of underwater light. Since both nutrients and water colour are frequently quantified as concentrations, it is important to recognise the importance of both total loads (masses) of delivered material and the flow volumes in which it is delivered. With reductions in flow, all else being equal, we might expect concentrations to increase, for instance.

Cyanobacterial growth rates frequently reach their maximum, or exceed those of other phytoplankton above a water temperature of 25°C (Paerl & Huisman, 2008; Jöhnk *et al* 2008). However, the temperature at which bloom formation occurs is often much lower due to other factors such as nutrient availability (total loading and resultant concentrations), and lake morphology. Recent studies by CEH (Carvalho et al. 2013; Van der Spoel 2019) suggest a water temperature of 17°C as a threshold above which blooms are more likely to occur in the UK, assuming sufficient nutrients are available to support primary production.

### 5.3.2 Impacts on natural assets and the services they provide

Blooms can bring about financial losses to the water industry, because of the costs of managing filter blockages and taste and odour in drinking water (Pretty et al. 2003), or the risk of shutting down entire water bodies used for public drinking supply. Furthermore, blooms can be a risk to public and animal health (Codd et al., 2005) and be unsightly, severely impacting upon recreational potential (site closures for water sports and fishing) (Carvalho et al., 2013; Sanseverino *et al* 2016).

### 5.3.3 Ecosystem assessment – climate hazard thresholds

An empirical relationship between monthly mean lake water temperature and air temperature was used to derive the air temperature threshold which corresponds with the water temperature threshold of 17 °C (see Appendix 1). In this assessment the number of months with monthly mean air temperatures exceeding a 14.7 °C threshold was calculated. The air temperature threshold differs because water has a high specific heat capacity.

Lakes receiving high nutrient levels are more at risk of developing algal blooms. We defined a category of 'high risk' of HAB development by quantifying the proportion of lakes in each region where the likelihood of cyanobacterial blooms exceeding WHO thresholds was >60%, based on nutrient inputs alone (Harrison et al. 2017). The underlying assessment made use of data from the Environment Agency and from SEPA[3] to calculate which UK lakes were receiving excess nutrient (phosphorus) inputs, and were, therefore, at risk of failing UK WFD water quality thresholds for total phosphorus (May et al. 2019). The phosphorus thresholds are site-specific and based on depth, alkalinity and altitude of individual lakes (WFD-UKTAG, 2016).

Below we show the average number of months per year (calculated over a decade) where mean monthly air temperatures exceed 14.7 °C (Table 4). All UK regions show a projected increase in the number of "hot months", where monthly water temperature exceeds the threshold. Scotland generally have a low incidence of such months. In contrast, "hot months" are projected to be especially frequent in London, East and South East England, for the 4°C scenario. These screening data suggest that under current climatic conditions, some areas such as East Scotland and North Scotland are unlikely to experience an increased risk of cyanobacteria blooms in response to warming. However, data from the 'Bloomin Algae' app[4], show there are confirmed incidences in these areas presently. Numbers of incidences recorded by the app. are generally higher in Scotland reflecting increased recorder effort there, but nonetheless show that under current conditions, algal blooms are already occurring in these low risk areas. This is because bloom risk in the UK is also affected by other factors, such as alkalinity, water colour and flushing rate (the time water takes to pass through a lake)

[3] Scottish Environment Protection Agency and database right 2015. All rights reserved

[4] https://www.ceh.ac.uk/algal-blooms/bloomin-algae

(Carvalho et al., 2011), which means blooms may still occur below a water temperature of 17 °C. There will be some uncertainty around risk predictions in this screening assessment based only on exceedance of temperature and nutrient thresholds. Therefore, the projections of increased frequency of algal bloom incidences in the future across the UK are plausible, and this assessment of impact can be considered conservative.

*Table 4.* **Average number of months per year where mean monthly water temperatures exceed a 17 °C threshold.** *Showing: baseline 2001-2010 period, 2°C scenario and 4°C scenario. Single year values for 2003 shown for comparison with a known 'hot year'. n.d. – No Data.*

| Region | No. of lakes | % lakes at high risk of HABs due to excess P input | 2003 | Baseline (2001-2010) | 2 °C | 4 °C |
|---|---|---|---|---|---|---|
| North West England | 1,857 | 13 | 2 | 1.1 | 2 | 3.1 |
| North East England | 671 | 0 | 2 | 0.5 | 1.2 | 2.4 |
| Yorkshire and Humber | 1,593 | 0 | 2 | 1.2 | 2.1 | 3.1 |
| West Midlands | 2,071 | 100 | 3 | 1.8 | 2.8 | 3.8 |
| East Midlands | 1,649 | 56 | 3 | 1.9 | 2.9 | 3.9 |
| East of England | 2,105 | 100 | 3 | 2.6 | 3.2 | 4.2 |
| South West England | 1,878 | 67 | 3 | 2 | 3 | 3.8 |
| South East England | 2,693 | 50 | 3 | 2.7 | 3.3 | 4.3 |
| London | 275 | 100 | 3 | 3.3 | 3.8 | 4.9 |
| Wales | 1,391 | 0 | 2 | 1.1 | 2.3 | 3.3 |
| North Scotland | 20,289 | 0 | 0 | 0 | 0 | 0.7 |
| West Scotland | 3,242 | 8 | 1 | 0.2 | 0.7 | 1.6 |
| East Scotland | 2,085 | 19 | 0 | 0 | 0.1 | 1.4 |
| Northern Ireland | 22 | 100 | 1 | 0.4 | 1.1 | 2.3 |
| England total/average | 14,792 | 54 | 2.7 | 1.9 | 2.7 | 3.7 |
| Wales total/average | 1,391 | 0 | 2.0 | 1.1 | 2.3 | 3.3 |
| Scotland total/average | 25,616 | 9 | 0.3 | 0.1 | 0.3 | 1.2 |
| Northern Ireland total/average | 22 | 100 | 1.0 | 0.4 | 1.1 | 2.3 |
| **UK total/average** | **41,821** | **43.8** | **2.00** | **1.34** | **2.04** | **3.06** |

### 5.3.4 Economic assessment – impact on goods and services

The economic impact of rising temperatures on incidences of algal blooms is calculated using estimates of costs of freshwater eutrophication from Pretty *et al.* (2003). The costs include impacts on provisioning services such as water supply, regulating services linked to water and air quality, and cultural services such as recreation and amenity, as well as direct impacts on biodiversity. We use the same cost categories as Pretty *et al.,* which are amongst only a small number of studies on the economic costs of freshwater eutrophication. The study uses a variety of methods to derive cost estimates and focuses on different costs borne by eutrophication rather than detailed estimates for single cost categories. Accordingly these figures represent estimates of the costs of observed outbreaks. In addition, the study does not account for the possibility that some cost categories could overlap and lead to double counting. Given the limited evidence of costs of eutrophication in the UK, we use these figures as best available evidence on the illustrative costs of algal blooms.

Pretty et al. (2003) estimate that the annual cost of algal bloom in the UK amounted to £114 million based on the incidence of blue-green algal blooms in waterbodies of England and Wales between 1990-1999. Over this period 3,993 incidences were reported across 2,710 waterbodies. The economic impacts from Pretty et al. (2003) for the period 1990-1999 relate only to England and Wales. These were scaled to the UK by including Scotland and Northern Ireland, with values weighted by population. The re-calculated costs for the period 2001-2010 for the UK and by impact category are given in Table 5. Annual costs over this period amount to £173 million, with the combined impacts on drinking water treatment costs of close to £60 million per year the largest cost category of algal bloom impacts. This is followed by large impacts on recreation opportunities on waterbodies, such as water sports, which total £50 million annually.

*Table 5. **Re-calculated annual costs of algal blooms from Pretty et al. (2003), scaled up to UK (£ million).** Breakdown provided by cost component.*

| Impact of algal bloom | Value (£m) |
|---|---|
| Value of waterside properties | 14.9 |
| Value of water bodies for commercial uses | 1.5 |
| Drinking water treatment costs (algal removal) | 28.8 |
| Drinking water treatment costs (nitrogen removal) | 30.5 |
| Clean up costs of waterways | 1.5 |
| Reduced value of non-polluted atmosphere | 12.1 |
| Reduced recreational and amenity value for water sports | 50.6 |
| Revenue losses for formal tourist industry | 17.7 |
| Revenue losses for fisheries | 0.2 |
| Ecological damage costs | 15.4 |
| **Total** | 173.3 |

Impacts at baseline are assumed to have the same economic value as those reported in Pretty et al. (2003), since this is based on observed incidences which includes the influence of other contributing factors such as nutrient inputs, management etc. Current levels of adaptation, and the influence of contributing factors are assumed constant over the assessment period. Impacts at UK level are disaggregated to region based on a combined weighting of climate risk (from Table 4) and population, since economic values are in most cases proportional to the population affected.

For future assessment periods, the economic cost at baseline is scaled according to future climate risk, i.e. by ratio of future number of months exceeded divided by number of months exceeded at baseline. This assumes that incidence of an algal bloom for 2 months has double the cost of an algal bloom lasting for 1 month. This is likely to apply in many of the cost estimates, e.g. loss of recreation opportunity. However, we recognise that in some estimates the impacts may not scale directly with duration. Impacts on biodiversity may be long lasting and increasingly severe with increasing duration, while clean up costs may represent a single cost regardless of duration.

To adapt these values to estimate the cost of future algal bloom outbreaks driven by rising temperatures, we adapt the estimates derived by Pretty *et al.* (2003) as follows:

**Step 1:** Calculate annual baseline damages of algal bloom for 2001-2010 baseline by adjusting for the change in consumer prices over time. These equate to an increase of 2.8% per year based on the level of consumer prices given by the Bank of England. This value was then scaled to a UK total from the England & Wales data reported in Pretty et al. (2003), as described above, using 2011 population data.

**Step 2**: Using estimates of monthly mean lake water temperatures exceeding 17°C under future temperature scenarios, calculate proportional increase in the average number of months where the water temperature threshold is exceeded, for each region.

**Step 3**: Using the assumption that the number of months of threshold exceedance drives the incidence of algal bloom outbreaks, we calculate the UK average change in number of months exceeded to estimate the proportional increase in costs under 2°C and 4°C scenarios. We assume that baseline damage levels (from Pretty et al. 2003) reflect the impact of contributing factors such as excess nutrient levels, as well as existing levels of adaptation, and that these are held constant into the future.

**Step 4**: To derive regional estimates, a weighted risk for each region is calculated using a combined weighting based on the population affected in each region (proportional weighting by population) and the ecological risk score (weights: High = 3, Medium =2, Low =1). The population affected is critical because most of the damage costs are linked to use (e.g. property values, drinking water, recreation, fishing, etc.). The regional weights are then used to disaggregate the final cost estimate.

Following the steps above, the estimated change in algal bloom outbreaks in the UK under future temperature scenarios is shown in Table 6. Compared with outbreaks in the period 2001-2010, threshold exceedance in a 2°C scenario implies that the number of outbreaks per year increases by 52%. For a 4°C scenario, the number of outbreaks is estimated to increase by 128%.

*Table 6.* ***The estimated change in algal bloom outbreaks in lakes in the UK due to temperature threshold exceedance***

| | **Baseline (2001-2010)** | **2 °C scenario** | **4 °C scenario** |
|---|---|---|---|
| UK average ratio of change in number of months exceeding the threshold, compared with 2001-2010 (& % change) | - | 1.52 (+52%) | 2.28 (+128%) |

The cost of algal bloom outbreaks under baseline, 2°C and 4°C scenarios is shown in Table 7. For the baseline period, total costs in the UK are £173 million per year. The cost increases to £295 million under 2°C scenario and to £481 million for a 4°C scenario. Most of these costs occur in England for three reasons. First, most waterbodies susceptible to HABs are in England implying higher baseline ecological risk. Second, the incidence of temperature threshold exceedance is greater in England increasing the risk of HABs in future. Third, economic costs are concentrated in more built up regions in England, such as the South East and Midlands, due to impacts on a greater number of people who use the waterbodies.

*Table 7.* ***Baseline (current) and projected economic costs (£ million) of estimated change in algal bloom outbreaks in the UK under 2 °C and 4 °C scenarios****. Regional impacts are allocated from the UK total using combined population and ecological risk weightings.*

| | Cost (£ million) | | |
|---|---|---|---|
| **Region** | **Baseline (2001-2010)** | **2 °C** | **4 °C** |
| North West England | 18.7 | 27.2 | 42.1 |
| North East England | 3.4 | 5.0 | 7.7 |
| Yorkshire and Humber | 7.0 | 10.2 | 15.8 |
| West Midlands | 14.9 | 32.3 | 50.2 |
| East Midlands | 12.0 | 26.2 | 40.6 |
| East of England | 23.2 | 33.7 | 52.2 |
| South West England | 13.9 | 30.4 | 47.1 |
| South East England | 34.2 | 49.6 | 77.0 |
| London | 32.6 | 47.3 | 73.4 |
| Wales | 4.0 | 5.9 | 9.1 |
| North Scotland | 0.5 | 0.7 | 1.1 |
| West Scotland | 3.4 | 4.9 | 15.1 |
| East Scotland | 3.1 | 4.5 | 14.0 |
| Northern Ireland | 2.3 | 6.8 | 15.8 |
| | | | |
| England total | 160.0 | 271.4 | 423.9 |
| Wales total | 4.0 | 6.1 | 9.5 |
| Scotland total | 6.9 | 10.4 | 31.4 |
| Northern Ireland total | 2.3 | 7.0 | 16.5 |
| **UK total** | **173.3** | **295.0** | **481.3** |

### 5.3.5 Adaptation

Warming is synergistic with the effects of the primary stressor, nutrients (Rigosi et al. 2014; Richardson et al. 2018). As nutrient concentrations have a dominant effect on the maximum capacity of algal standing crop in a lake (Carvalho et al., 2013), adaptation that primarily focuses on nutrient management will, therefore, reduce the size of the effect that temperature can have on algal biomass. This includes local management of nutrient loadings entering lakes through catchment management or enhanced (tertiary) wastewater treatment processes. Mitigation measures may also be available where catchment measures are insufficient to deliver nutrient reductions necessary in the timescales of our projections. For example, approaches to limit the “internal” supply of nutrients from lake bed sediments have been trialled with mixed success to control in-lake phosphorus concentrations (Spears et al., 2018) and to reduce cyanobacteria abundance (Lürling et al., 2016). Disruption of increasingly stable water columns through aeration and artificial mixing may also offer relief from the physical effects of increased temperature, especially in deep stratifying lakes (Visser et al., 2016; Gibbs and Howard-Williams, 2018). Biomanipulation of the fish community to release zooplankton from predation has been demonstrated to reduce algal concentrations even at elevated phosphorus concentrations, for example in the shallow lakes of the Norfolk Broads (Phillips et al., 2015). If possible, the manipulation of water residence time is a potential approach for reducing nutrient concentrations (Spears et al., 2006) and cyanobacteria (Reynolds et al., 2002; Mantzouki et al. 2016) to off-set warming. There are some options to mitigate post-bloom impacts by additional processes to make drinking water safe; these incur increased water treatment costs.

All of these measures require more research to confirm their efficacy in more effectively mitigating the effects of climate change and will be context dependent. It is likely that combinations of adaptation (to a changed climate) and mitigation (of climate impacts) approaches may increase effectiveness. Adaptation approaches are summarised in Table 8.

Key adaptations that have been proposed to reduce the potential negative impact of agriculture on waterways include:

- smarter targeting of fertiliser type and application (NAP);
- increased nitrogen use efficiency (Net Zero);
- extending existing regulation to reduce on-farm emissions, for example through extending Nitrogen Vulnerable Zones Key (Net Zero); and
- encouraging low carbon farming practices such as using precision farming for crops, manure planning, and using controlled release fertilisers (Net Zero).

As nutrient concentrations have a dominant effect on the maximum capacity of algal standing crop in a lake (Carvalho et al., 2013), if nutrients are reduced, the impact of increased temperature on algal blooms will be lessened, but not removed entirely due to legacy phosphorus incorporated in lake sediments. Carvalho et al. (2013), indicate that the likelihood for developing a bloom is greatly minimised below a threshold of about 20 μg/L total phosphorus in lake water. Nutrients could be reduced through reducing run-off from agriculture, for example through precision application, or by creating a buffer strip around the field and the lake to reduce instances of pollutants reaching the water. Measures such as these can be implemented to mitigate the risk of nutrients reaching the water body, which would reduce the likelihood of algal blooms as the threshold is approached. If the threshold is crossed, and nutrient levels are sufficient for algal blooms to develop, in-lake mitigation measures and water treatment options may be able to mitigate against the impact.

*Table 8. Adaptation approaches for temperature impacts on algal blooms in lakes*

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Local nutrient management to prevent nutrients from entering the lake – this could include reducing run-off from agriculture and enhancing wastewater treatment. | Agri-environment schemes and rules for farmers are in place to reduce instances of agricultural nutrients running off into watercourses. Rules apply to those receiving funding under CAP pillar 1 and pillar 2 as well as those within nitrate vulnerable zones.<br><br>Nutrient management guides such as RB209 assist farmers in reducing pollution risks.<br><br>The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018 came into force in April 2018 (CCC 2019). Monitoring data is gathered by the Environment Agency. In Scotland this is controlled by the Water Environment (Diffuse Pollution) (Scotland) Regulations 2008 and the Water Environment (Controlled Activities) (Scotland) Regulations 2011. | There has been an increase in the number of freshwater sites of specific scientific interest (SSSIs) in favourable condition but the proportion of surface water bodies in high or good ecological status, has reduced (CCC 2019). | **Delivering adaptation:**<br><br>Regulation: Restricting the land use around lakes could help to prevent nutrients from entering the water. This could include buffer strips for agricultural production or withholding this land area for tree planting.<br><br>Advice: Where farmers recognise the private benefits of precise nutrient management, information and advice can change behaviours and drive autonomous adaptation.<br><br>Incentives: There are challenges to internalising costs within a farm business as well as allocating costs as the source of numerous small pollution incidents are not easily identifiable. Therefore grants may be required to assist farmers with nutrient management. If land near the lake is to be taken out of | **Delivering adaptation:**<br><br>Implementing (or improving) nutrient management practices to reduce the amount of nutrients which reach watercourses will have an immediate benefit. However, further adaptation such as land use change (buffer strips, afforestation etc.) may be required to have a greater impact. Combining these land management changes with water management practices (e.g. chemical nutrient management, mixing and aeration) may be able to delay the threshold. Early action decreases water pollution and reduces the risk of lock-in; |

| | | | | |
|---|---|---|---|---|
| | The National Environment Programme includes schemes to improve discharge from sewage (CCC 2019). This aims to reduce the risk of eutrophication and improve the quality of discharge water.<br><br>In England, the Water Environment Grant Scheme for improving the water environment (administered by the EA and Natural England, supported by EAFRD, and part of RDPE) was launched in 2018/19. | | agricultural production compensation may be required.<br><br>**Building capacity:**<br><br>There is huge scope for improving awareness of future climate change impacts and adaptation response associated with nutrients in watercourses. This needs to be targeted spatially and focused on the economic case as well as the public good aspect.<br><br>Land management techniques to limit the amount of nutrients which get in to watercourses are widely available (e.g. wastewater treatment, precision application of nutrients, buffer strips etc.). Capacity is therefore largely available, but action depends on the incentives or regulation in place. Increasing capacity may be required for actions related to internal loading control, bio-manipulation, aeration, mixing, and floating solar panels. | therefore timely action is important.<br><br>The new environmental land management schemes in the UK post-Brexit[5] will apply from 2023, and are likely to include measures to reduce diffuse nutrient pollution. However, such adaptation options need to be clearly built into design and piloting [2019-2023]. Changes to regulation and advice provision are also being developed as part of Defra’s 25YEP.<br><br>**Building capacity:**<br><br>Small changes in land management can have a big impact on nutrient runoff which can then reduce algal blooms in watercourses as temperatures increase. Building capacity in mitigation practices such as internal load control, flocculation of cyanobacteria, bio-manipulation, aeration, mixing and covering will help to |
| Changing the conditions within the lake, for example, increasing the flushing rate during summer. | Not currently widely practiced. | N.A | | |
| Shading the water to prevent warming, for example this could include solar panels on top of the lake. | Not widely practiced, but some examples of solar power generation on lakes, e.g. Langthwaite Reservoir in Lancashire, and the Queen Elizabeth II reservoir near Heathrow. | N.A | | |

[5] Environmental Land Management Scheme in England, the Sustainable Land Management Scheme in Wales, and the developing schemes in Scotland and Northern Ireland

| | | | | |
|---|---|---|---|---|
| | | | | provide additional options where nutrient management is not sufficient to prevent algal blooms. As there could be a long lead time in the development of these options, taking action to review their effectiveness and develop planning and implementation procedures should be a priority in the next five years. |

**Is risk managed by autonomous or planned adaptation?**

Planned adaptation will be required to manage the risk. Adaptation benefits are largely for the public good, although there may be private interest, for example for the water industry. Nutrient management can mitigate against the production of algal blooms. If nutrients become a limiting factor, algal blooms may not be able to form despite an increase in temperature. However, it is unlikely that all nutrients would be prevented from reaching watercourses. In these cases, water treatment options can help to reduce the impact of algal blooms.

**Risks of lock-in**

Land use change near the lake may create lock in.

Potential loss of aquatic species if the threshold is crossed.

**Risk(s) interacting**

Water quality reduction if algal blooms increase, but increase in water quality through adaptation options

Biodiversity losses from algal blooms

| |
|---|
| Soil health will likely improve due to precision application of nutrients; there may also be reduced erosion risk due to buffer strips etc. |
| **Urgency scoring**<br><br>More urgent: more action needed – planned adaptation will be required to reduce the impact of the threshold, with implementation needed above levels already planned. Capacity is available to prevent nutrient loading and benefits from implanting this adaptation will be seen within the next five years. Further research is urgently required to identify effective suites of mitigation measures which are not currently widely practiced (e.g. combinations of: hydrological control, aeration and artificial mixing, chemical removal of nutrients and cyanobacteria; biomanipulation). |

**What is the impact of current levels of adaptation at mitigating these risks?**

Catchment-wide management of nitrogen and phosphorus diffuse sources and improved management of point sources, often domestic sewage, are the primary mechanisms for altering the pre-conditions for algal bloom formation. These are applied in nitrate vulnerable zones, but not widely elsewhere. They have been trialled as a response to requirements for Water Framework Directive compliance and for protecting species, but have not specifically been introduced to mitigate climate change impacts. Other aspects such as chemical remediation have been trialled in a limited number of severely affected water bodies, but not widely. Other management aspects such as riparian shading of lakes and input rivers have received relatively little focus so far. Few, if any, studies have assessed the effectiveness of these approaches to mitigate climate change effects on algal blooms in the UK.

In England, there has been an increase in the number of freshwater Sites of Special Scientific Interest (SSSIs) in favourable condition: 47% in 2018, compared to 42% in 2016 (CCC 2019). However, looking at all surface water bodies in England, in 2017, only 16% of surface water bodies assessed under the Water Framework Directive were in high or good ecological status, compared to 24% in 2012 (CCC 2019). In Scotland, in 2014, 66% of all water bodies were classified as being in good or better condition, with this rising to 83% when only looking at protected water bodies (Scottish Government, 2015). These figures can be used as an indication of the impact of adaptation (minimal), however factors beyond phytoplankton blooms, such as fish, macro-invertebrate, macrophyte and diatom populations, hydromorphology, and levels of heavy metals, pesticides, dissolved oxygen and other supporting elements, will be considered in these assessments so this is not a direct link to adaptation. It is clear that more stringent nutrient targets will be necessary to account for the effects of climate change to deliver necessary ecological responses, where this can be achieved. Current nutrient targets across UK lakes do not include a climate change factor.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

The measures discussed in the previous section could be applied much more widely to reduce the likelihood of preconditions being favourable for algal bloom formation. Management of nutrient sources to reduce the external nutrient input is considered the most effective way of preventing the formation of algal blooms (Visser *et al.,* 2016). This includes pathways from agriculture but also from waste water discharges and attention should be given to effective regulation and water company planning. Although not widely practiced, aeration, artificial mixing, and chemical remediation could be used to reduce the impacts of algal blooms once they have formed. For example, in some lakes, artificial mixing may be effective in preventing blooms of cyanobacteria, and shifting the phytoplankton composition from cyanobacteria to diatoms and green algae (Visser *et al.,* 2016). Furthermore, wider application of fish biomanipulation approaches could be explored. However, the economic burden of such approaches, i.e. the continuous mitigation of symptoms, will be high, and unintended ecological consequences must be fully assessed before widespread application. Therefore, such measures are, currently, likely to be unsustainable as a general approach.

**In what scenarios are there limits to adaptation?**

The adaptation methods apply in most cases to the pre-conditions necessary for algal bloom formation, therefore they are to a large extent independent of the climate risk. However, the geographical pattern of climate risk will dictate the number of water bodies that need to be considered for management. Lack of incentives or regulation may limit adoption of adaptation actions (e.g. nutrient management/buffer strips) by land owners, which would impact on the ability to prevent formation of algal blooms. There are also challenges due to tracing the source of diffuse pollution, and establishing co-operation and joined up action at a catchment scale.

There may be limits to adaptation once severe phytoplankton blooms have established. Attempts to restore the lake could include removing nutrients, artificial mixing, aeration, introduction of surface feeders and plants which will take up nutrients, and removal or re-introduction of fish (depending upon the trophic level of the fish species in question). However, depending on local conditions, and likelihood/frequency of the algal bloom re-establishing, restoration may not be appropriate. The larger the lake, and more severe the algal bloom, the more challenging adaptation can be. Ultimately, if the nutrient sources cannot be controlled, which may be the case in large parts of the UK, there is little value in implementing other adaptation options.

## 5.4 Temperature effects on phytoplankton blooms in rivers

Figure 7 below summarises the threshold and assessment chain. River water temperatures are likely to warm in line with air temperature. Above a monthly mean water temperature of 19 °C there is an increased risk of algal blooms developing, with a resulting decrease in water quality, and impacts on the ecosystem services that depend on good water quality.

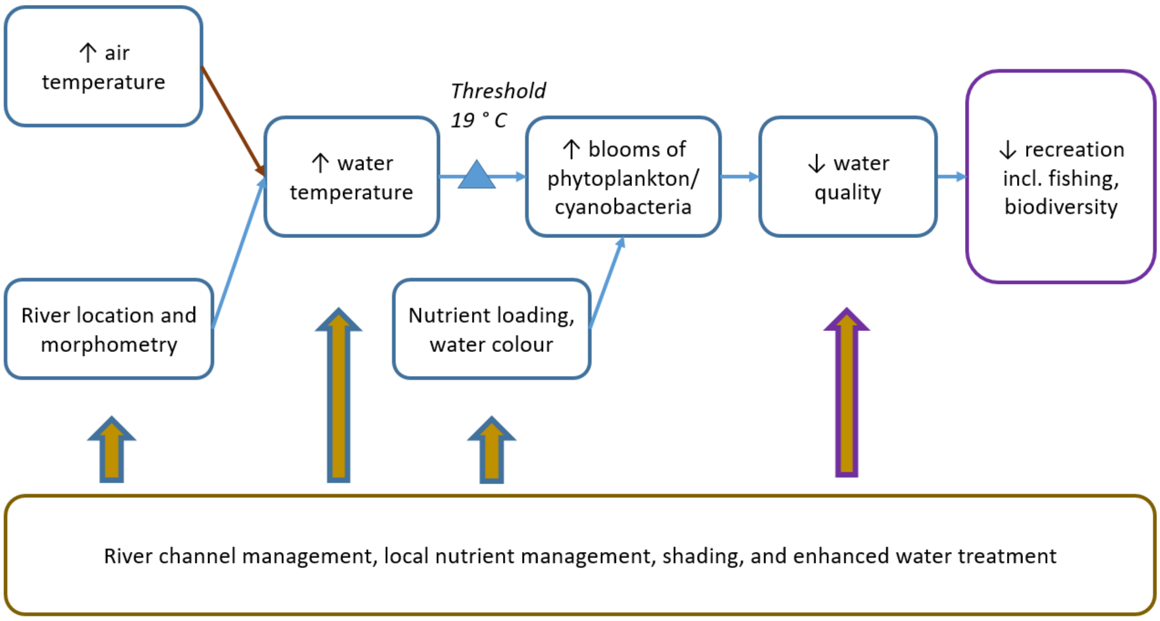


*Figure 7.* **Impact chain for temperature effects on phytoplankton blooms in rivers.** *Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures.*

### 5.4.1 Justification of threshold used in the assessment

In river ecosystems, river water temperatures are likely to warm in line with air temperature, which in turn stimulate the growth of algal species capable of forming blooms (Bowes *et al* 2016; Charlton et al. 2018). A monthly mean water temperature threshold of 19°C for impacts on rivers is described in Bowes *et al* (2016). This temperature represents an important physical control on phytoplankton growth, but many other factors interact with temperature to affect bloom occurrence and magnitude in the field. Rapid flows can potentially flush algae from the river channel and reduce blooms (Salmaso & Zignin 2010). Therefore, as a result of hydrological flushing, we expect that climate-driven bloom formation would be most likely for lowland rivers, with slower flows. Bloom duration and magnitude is governed by nutrient availability as well as water temperature and flow.

### 5.4.2 Impacts on natural assets and the services they provide

Blooms can bring about financial losses to the water industry, because of the costs of managing filter blockages, water taste and odour. Furthermore, blooms can be a public health risk, and be unsightly, impacting upon recreational potential.

### 5.4.3 Ecosystem assessment – climate hazard thresholds

In the absence of a relationship between air temperature and river water temperature, we assume equivalence of air temperatures with water temperature for lowland rivers. Therefore, this assessment calculates the average number of months per year with mean monthly air temperatures above 19°C, and summarises these data over UK regions.

Below we show the average number of months per year with mean water temperatures exceeding 19 °C for each scenario period (Table 9). All UK regions show an increase in the number of months exceeding the threshold in a warming world.

*Table 9. **Average number of months per year where projected monthly mean air temperatures exceed a 19 °C threshold in 2003, and under baseline, 2 °C and 4 °C scenarios**. 2003 shown for comparison with a previous 'hot year'. n.d. = No Data*

| Region | Lowland river length (km) | Number of months exceeding temperature threshold | | | |
|---|---|---|---|---|---|
| | | 2003 | Baseline (2001-2010) | 2 °C | 4 °C |
| North West England | 12,022 | 1 | 0.1 | 0.2 | 1.4 |
| North East England | 8,943 | 0 | 0 | 0 | 1 |
| Yorkshire and Humber | 8,823 | 1 | 0.2 | 0.8 | 2 |
| West Midlands | 8,507 | 2 | 0.7 | 1.3 | 2.8 |
| East Midlands | 5,090 | 2 | 0.8 | 1.5 | 2.9 |
| East of England | 1,271 | 2 | 1.2 | 2.2 | 3.2 |
| South West England | 10,537 | 2 | 0.8 | 1.5 | 2.9 |
| South East England | 3,256 | 2 | 1.2 | 2 | 3.3 |
| London | 40 | 3 | 2.1 | 3.1 | 4.1 |
| Wales | 20,099 | 1 | 0.2 | 0.5 | 1.6 |
| North Scotland | 43,445 | 0 | 0 | 0 | 0.2 |
| West Scotland | 26,632 | 0 | 0 | 0 | 0.6 |
| East Scotland | 25,945 | 0 | 0 | 0 | 0.6 |
| Northern Ireland | n.d. | 0 | 0 | 0 | 1 |
| | | | | | |
| England total/average | 58,488 | 1.7 | 0.8 | 1.4 | 2.6 |
| Wales total/average | 20,099 | 1.0 | 0.2 | 0.5 | 1.6 |
| Scotland total/average | 96,022 | 0.0 | 0.0 | 0.0 | 0.5 |
| Northern Ireland total/average | n.d. | 0.0 | 0.0 | 0.0 | 1.0 |
| **UK total/average** | **174,609** | **1.1** | **0.5** | **0.9** | **2.0** |

England increases from an average of 0.8 months per year at baseline, to 1.4 months in a 2 °C scenario and 2.6 months in a 4 °C scenario. Wales has fewer months exceeding the threshold, with 0.2 at baseline, increasing to 1.6 months in a 4 °C scenario. Scotland and Northern Ireland do not exceed the temperature threshold at baseline or in a 2 °C scenario, but do so in the 4 °C scenario.

### 5.4.4 Economic assessment – impact on goods and services

Economic analysis has not been possible for algal blooms in rivers/canals. Pretty et al. (2003) do not differentiate between water body types in their analysis. There is evidence that slower moving (i.e. lowland) rivers and canals also suffer from algal blooms, and may be at equal risk to lakes and still water. Not all of the costs in Pretty et al. (2003) are applicable to rivers and canals, for example drinking water abstraction is primarily from reservoirs or groundwater rather than rivers. The type and value of recreation is likely to be different in lowland rivers compared with lakes. Further work would be required to provide a robust valuation of this impact.

### 5.4.5 Adaptation

Riparian planting to shade channels provides a mechanism for reducing incident light and water temperature. Trees and shrubs reduce summer mean and maximum water temperatures, on average, by 2$^{o}$C to 3$^{o}$C in shaded areas (Woodland Trust, 2016), and this effect extends downstream. Therefore this adaptation measure can be used to delay exceedance of the threshold. Managing flow conditions by removing barriers and impoundments can also help reduce build-up of phytoplankton blooms in particular areas. Adaptation approaches are summarised in Table 10.

NAP actions include:

- Smarter targeting of fertiliser type and application in order to reduce the potential for negative impact of agriculture on waterways;
- Explore the potential for new innovative and sustainable fertilisers, such as bio-stimulants, to improve nutrient use efficiency; and
- Implement the Site Improvement Plans (SIPs), including actions arising from the climate change theme plan we have developed for Natura 2000 sites.

Note that no plans are in place that consider adaptation to higher water temperatures in meeting WFD targets. Net Zero pathways for agriculture include plans to reduce $N_2O$ emissions through increased nitrogen use efficiency; hence reducing nitrate loss to water. Key actions included within CCC (2020) include extending existing regulation to reduce on-farm emissions, for example through extending Nitrogen Vulnerable Zones, and encouraging low carbon farming practices such as using precision farming for crops, manure planning, and using controlled release fertilisers. If nutrients are limited, the impact of increased temperature on algal blooms is lessened. Nutrients could be reduced through reducing run-off from agriculture through precision application, or by creating a buffer strips around fields and along rivers, or targeting waste water treatment works to reduce loadings of nutrients reaching the water. Measures such as these can be implemented to mitigate the risk of nutrients reaching the water body, which would reduce the likelihood of algal blooms as the threshold is exceeded.

*Table 10. **Adaptation approaches for temperature impacts on algal blooms in rivers***

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Local nutrient management to prevent nutrients from entering the river – this could include reducing run-off from agriculture and enhancing wastewater treatment. | Agri-environment schemes are in place to reduce instances of agricultural nutrients running off into watercourses. Rules apply to those receiving funding under CAP pillar 1 and pillar 2 as well as those within nitrate vulnerable zones.<br><br>Nutrient management guides such as RB209 assist farmers in reducing pollution risks.<br><br>The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018 came into force in April 2018 (CCC 2019). Monitoring data is gathered by the Environment Agency. In Scotland this is controlled by the Water Environment (Diffuse Pollution) (Scotland) Regulations 2008 and the Water Environment (Controlled Activities) (Scotland) Regulations 2011. | The 2015 River Basin Management Plans confirmed over £3 billion investment over 6 years. Over 1,400 miles of surface water has been enhanced towards a target of nearly 5,000 miles by 2021 (CCC 2019). There has been an increase in the number of freshwater sites of specific scientific interest (SSSIs) in favourable condition but the | **Delivering adaptation:**<br><br>Regulation: Restricting land use around the river could help to prevent nutrients from entering the water. This could include buffer strips for agricultural production or withholding this land area for tree planting.<br><br>Incentives: There are challenges internalising costs within a farm business as well as allocating costs as the source of numerous small pollution incidents are not easily identifiable. Therefore grants may be required to assist farmers with nutrient management. If land near the river is to be taken out of agricultural production, and used for riparian planting or buffer strips, compensation may be required.<br><br>**Building capacity:** | **Delivering adaptation:** Implementing (or improving) nutrient management practices will have benefits within the next five years in terms of the amount of nutrients which reach watercourses. However, further adaptation such as land use change (buffer strips, tree planting etc.) may be required to have a greater impact. Early action decreases water pollution and reduces the risk of lock-in; therefore timely action is important. This should involve some assessment of priority sites where actions can be effective and represent best value for money.<br><br>The new environmental land management schemes in the UK post-Brexit[6] will apply from 2023, and are likely to include |

[6] Environmental Land Management Scheme in England, the Sustainable Land Management Scheme in Wales, and the developing schemes in Scotland and Northern Ireland

<table>
<tr>
<td></td>
<td>River Basin Management Plans are required by the Water Framework Directive to ensure that all ‘defined water bodies’ meet ‘good status’ by 2021, or by 2027 where this is not possible (CCC 2019).<br><br>The National Environment Programme includes schemes to improve discharge from sewage (CCC 2019). This aims to reduce the risk of eutrophication and improve the quality of discharge water.<br><br>In England, the Water Environment Grant Scheme for improving the water environment (administered by the EA and Natural England, supported by EAFRD, and part of RDPE) was launched in 2018/19.</td>
<td>proportion of surface water bodies in high or good ecological status, has reduced (CCC 2019).</td>
<td rowspan="2">There is huge scope for improving awareness of future climate change impacts and adaptation response associated with nutrients in watercourses. This needs to be targeted spatially and focused on the economic case as well as the public good aspect.<br><br>Where farmers recognise the private benefits of precise nutrient management, information and advice can change behaviours and drive autonomous adaptation.<br><br>Land management techniques to limit the amount of nutrients which get in to watercourses are widely available (e.g. wastewater treatment, precision application of nutrients, buffer strips etc.). Likewise capacity is available for planting trees to shade rivers. Capacity is therefore largely available, but action depends on the incentives or regulation in place, and should be targeted to areas where the greatest benefit for water quality is likely to be achieved.</td>
<td rowspan="2">measures to reduce diffuse nutrient pollution. However, such adaptation options need to be clearly built into design and piloting [2019-2023]. Changes to regulation and advice provision are also being developed as part of Defra’s 25YEP.<br><br>Building capacity:<br><br>Small changes in land management can have a big impact on nutrient runoff which can then reduce algal blooms in watercourses as temperatures increase. Similar changes, e.g. planting trees can also easily create shade to help reduce water temperatures. Actions around nutrient management and riparian planting can reduce the instances of algal blooms; preventing these from occurring in the first place is a better course of action than trying to mitigate the impacts once these are present.</td>
</tr>
<tr>
<td>Riparian planting to shade channels</td>
<td>Four year (2012-2016) Environment Agency led climate change adaptation project ‘Keeping Rivers Cool’. Guidance manual from the Woodland Trust (2016) on creating riparian shade for climate change adaptation.</td>
<td>N.A</td>
</tr>
</table>

| | | | | |
|---|---|---|---|---|
| | | | | |

**Is risk managed by autonomous or planned adaptation?**

Planned adaptation will be required to manage the risk. Adaptation benefits are largely for the public good, although there may be some private interest, for example for the water industry. Nutrient management can mitigate against the production of phytoplankton and algal blooms; if nutrients become a limiting factor then algal blooms are unable to form despite an increase in temperature. However, it is unlikely that all nutrients would be prevented from reaching the river, so this will not entirely eradicate the impacts of the threshold. Tree planting can reduce maximum river temperatures by 2-3$^{o}$C in shaded areas compared to open areas, therefore this mechanism will mitigate the impacts of the threshold, but only in shaded areas. However, no plans in place currently that address risks from higher water temperatures.

**Risks of lock-in**

Taking land out of production near the river/ planting trees along the river bank may create lock in

Potential loss of aquatic species if the threshold is crossed

**Risk(s) interacting**

Water quality reduction if algal blooms increase, but increase in water quality through adaptation options

Biodiversity losses from algal blooms

Soil health will likely improve due to precision application of nutrients; there may also be reduced erosion risk due to buffer strips etc.

**Urgency scoring**

More urgent: more action needed – planned adaptation will be required to reduce the impact of the threshold, with implementation needed above levels already planned. Capacity is available to prevent nutrient loading, and benefits from implementing this adaptation will be seen within the next five years.

**What is the impact of current levels of adaptation at mitigating these risks?**

There is currently no planning to reduce impacts of higher water temperatures. Current actions are relevant to the pre-conditions for algal bloom formation. Catchment-wide management of nitrogen and phosphorus diffuse sources and improved management of point sources, often domestic sewage, are the primary mechanisms for altering the pre-conditions for algal bloom formation. These are applied in nitrate vulnerable zones, but not widely elsewhere. Other management aspects such as riparian planting to shade river channels have received relatively little focus so far.

There has been an increase in the number of freshwater sites of specific scientific interest (SSSIs) in favourable condition but the proportion of surface water bodies in high or good ecological status, has reduced (CCC 2019). Over 1,400 miles of surface water has been enhanced towards a target of nearly 5,000 miles by 2021 (CCC 2019). These figures can be used as an indication of the impact of adaptation, however factors beyond phytoplankton blooms, such as fish, macro-invertebrate, macrophyte, and diatom populations, hydromorphology, and levels of heavy metals, pesticides, dissolved oxygen and other supporting elements will be considered in these assessments so this is not a direct link to adaptation.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Nutrient management could be applied much more widely to reduce the likelihood of preconditions being favourable for algal bloom formation. Management of nutrient sources to reduce the external nutrient input is considered the most effective way of preventing the formation of algal blooms (Visser *et al.,* 2016). This should consider the dominant source of nutrients, e.g. waste water versus agricultural diffuse pollution. Riparian planting can also be used to keep rivers below temperatures at which algal blooms form.

**In what scenarios are there limits to adaptation?**

The adaptation methods apply in most cases to the pre-conditions necessary for algal bloom formation, therefore they are to a large extent independent of the climate risk. However, the geographical pattern of climate risk will dictate the number of water bodies that need to be considered for management. Lack of incentives or regulation may limit adoption of adaptation actions (e.g. nutrient management/buffer strips/riparian planting) by land owners, which would impact on the ability to prevent formation of algal blooms. There are also challenges due to tracing the source of diffuse pollution, and establishing co-operation and joined up action at a catchment scale.

There may be limits to adaptation once severe phytoplankton blooms have established. Depending on local conditions, and likelihood/frequency of the algal bloom re-establishing, restoration may not be appropriate. Ultimately, if the nutrient sources cannot be controlled, there is little value in implementing other adaptation options. Targeted action is therefore critical.

## 5.5 Temperature effects on fish habitat volume in lakes

Figure 8 below summarises the threshold and assessment chain. Increased air temperatures lead to increased lake water temperatures. Above a threshold mean monthly lake water temperature of 18 °C increased phytoplankton and lower dissolved oxygen lead to a decrease in the thermally suitable habitat for rare fish species, such as the vendace. This may lead to extinction of this species in the UK, and to a loss in the ecosystem services these fish provide, including recreational fishing.

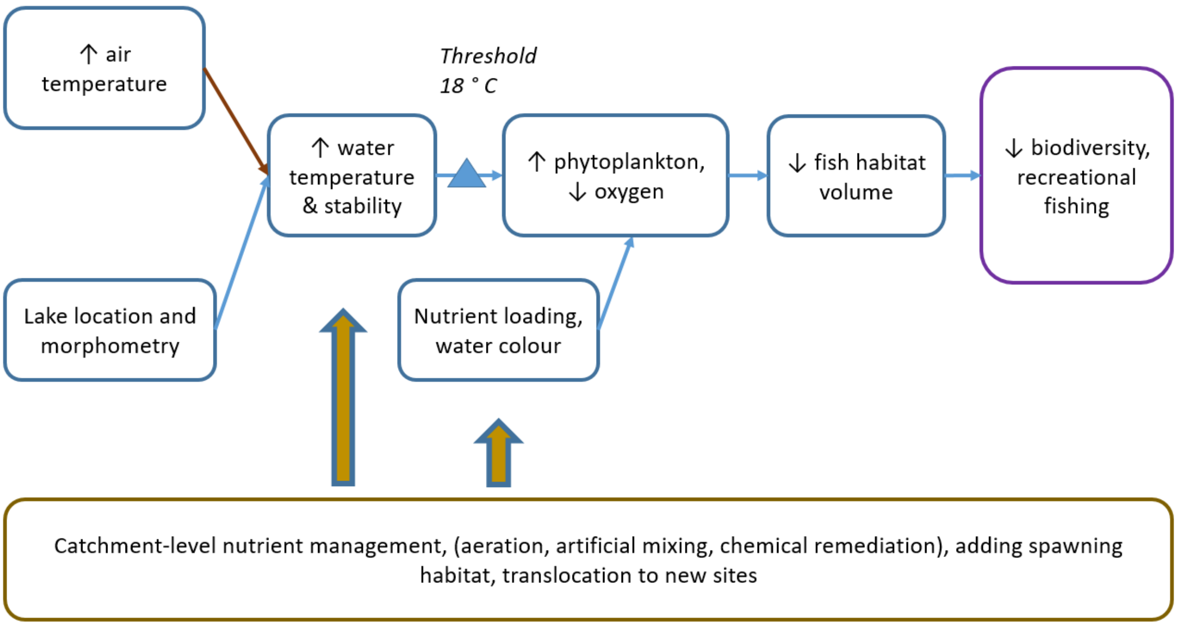


*Figure 8. **Impact chain for temperature effects on fish habitat volume in lakes**. Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures.*

### 5.5.1 Justification of threshold used in the assessment

The vendace is a freshwater fish species which is a relic of the last ice age and is highly sensitive to elevated temperatures (Winfield *et al* 2004). In the UK it is a rare species of conservation concern (Waters et al. 2018). Increasing air temperatures will contribute to increasing water temperatures. Coincident increases in water column stability (i.e. stronger thermal stratification) and temperature driven-increases in plankton populations result in reduced deep-water oxygen concentrations. Cold-water fish species of conservation value, such as the vendace, cannot tolerate such changes, and so they are excluded from areas with high temperatures and low oxygen (Stefan *et al* 2001, Elliott & Bell 2011). Excessive phytoplankton growth can also result in the siltation of fish spawning areas, by sinking plankton (Winfield *et al* 2008). Nutrient loading stimulates plankton growth, and can worsen oxygen depletion and spawning ground siltation further. In addition, climate warming may facilitate the expansion of non-native species that can compete with vendace for shared food resources (e.g. Elliott *et al* 2015), and further increase the pressures faced by current populations. A threshold mean monthly water temperature of 18°C represents a physiological constraint on the vendace, above which it is unlikely to persist (Winfield *et al* 2004). Different fish species have different physiological thresholds with respect to temperature, and would need their own assessments.

### 5.5.2 Impacts on natural assets and the services they provide

If the threshold defining the thermal habitat volume (its climate space) available for the vendace is exceeded in the lakes where it currently persists, it may be driven to extinction. Such changes would result in a loss of biodiversity, and would impact on recreational potential.

### 5.5.3 Ecosystem assessment – climate hazard thresholds

An empirical relationship between lake water temperature and air temperature was used to derive an air temperature threshold from the monthly lake water temperature threshold of 18 °C (see Supplementary Methods). Therefore, in this assessment the number of months with monthly mean air temperatures exceeding a 15.6 °C threshold was calculated.

Below we show the average number of months per year with mean monthly water temperatures exceeding 18 °C for each scenario period (Table 11). All UK regions show an increase in the number of months exceeding the threshold in a warming world.

*Table 11. **Average number of months per year where monthly mean water temperatures exceed a 18 °C threshold, in 2003, baseline, 2°C and 4°C scenarios**. Data for 2003 is shown for comparison with a previous 'hot year'.*

| Region | Number of months exceeding threshold | | | | Vendace present |
|---|---|---|---|---|---|
| | 2003 | Baseline (2001-2010) | 2 °C | 4 °C | |
| North West England | 2 | 0.4 | 0.8 | 2.2 | Present |
| North East England | 1 | 0.2 | 0.5 | 1.6 | |
| Yorkshire and Humber | 2 | 0.9 | 1.3 | 2.6 | |
| West Midlands | 2 | 1.2 | 2.2 | 3.3 | |
| East Midlands | 2 | 1.2 | 2.2 | 3.1 | |
| East of England | 2 | 1.6 | 2.9 | 3.9 | |
| South West England | 2 | 1.2 | 2.2 | 3.5 | |
| South East England | 3 | 1.7 | 2.9 | 3.9 | |
| London | 3 | 3 | 3.3 | 4.4 | |
| Wales | 2 | 0.5 | 1 | 2.4 | |
| North Scotland | 0 | 0 | 0 | 0.3 | |
| West Scotland | 0 | 0 | 0 | 1.1 | Present |
| East Scotland | 0 | 0 | 0 | 0.7 | |
| Northern Ireland | 0 | 0.1 | 0.6 | 1.4 | |
| England (average of regions) | 2.1 | 1.3 | 2.0 | 3.2 | Present |
| Wales (average of regions) | 2.0 | 0.5 | 1.0 | 2.4 | |
| Scotland (average of regions) | 0.0 | 0.0 | 0.0 | 0.7 | Present |
| Northern Ireland (average of regions) | 0.0 | 0.1 | 0.6 | 1.4 | |
| **UK (average of regions)** | **1.5** | **0.9** | **1.4** | **2.5** | **Present** |

Vendace is only present in two regions: north west England and west Scotland. In north west England the number of months exceeding the threshold increases from 0.4 at baseline to 0.8 in a 2 °C scenario and 2.2 in a 4 °C scenario, resulting in a change from low ecological risk to high. In west Scotland, temperatures only exceed the threshold in the 4 °C scenario, where risk increases from low to medium.

### 5.5.4 Economic assessment – impact on goods and services

It was not possible to calculate an economic assessment for impacts on vendace, since the recreation value and conservation value of this species are not sufficiently studied.

### 5.5.5 Adaptation

NAP actions include:

- introduce a sustainable fisheries policy as we leave the Common Fisheries Policy and prepare marine plans that include policies for climate adaptation; and
- build ecological resilience on land, in our rivers and lakes and at sea.

The Fisheries Bill [HL] 2019-21[7] has a climate change objective which seeks to ensure that:

a) the adverse effect of fish and aquaculture activities on climate change is minimised, and
b) fish and aquaculture activities adapt to climate change.

However, the provisions of the legislation are focused on sea fishing and there are no specific adaptations listed that relate to rivers and lakes.

Local nutrient management can partially offset issues of oxygen depletion, though not temperature increase. NAP actions to improve water quality and reverse the deterioration of groundwater are relevant, namely:

- Smarter targeting of fertiliser type and application in order to reduce the potential negative impact of agriculture on waterways; and
- Explore the potential for new innovative and sustainable fertilisers, such as bio-stimulants, to improve nutrient use efficiency.

Net Zero pathways for agriculture also include plans to reduce $N_2O$ emissions through increase nitrogen use efficiency; hence reducing nitrate loss to water. Key actions included within CCC (2020) include extending existing regulation to reduce on-farm emissions, for example through extending Nitrogen Vulnerable Zones, and encouraging low carbon farming practices such as using precision farming for crops, manure planning, and using controlled release fertilisers. If nutrients are limited, this can reduce the impact of nutrient loading and hence the impacts of increased phytoplankton and oxygen depletion. Nutrients could be reduced through reducing run-off from agriculture through precision application, or by creating a buffer strip around fields and the lake to reduce loadings of nutrients reaching the water. Measures such as these can be implemented to mitigate the risk of nutrients reaching the water body, which would reduce the likelihood of algal blooms and decreased oxygen as the threshold is approached.

[7] https://services.parliament.uk/bills/2019-21/fisheries.html

Approaches to limit the “internal” supply of nutrients from lake bed sediments can also be used to mediate the effects of climate change, including chemical remediation to lock-up phosphorus. Disruption of increasingly stable water columns through aeration and artificial mixing may also offset temperature-driven bloom increases to some extent. Shading, for example through use of solar panels is not considered appropriate for conserving these rare species. The manipulation of water residence time is being explored as an approach for cyanobacterial control. However, more interventionist approaches such as artificial aeration, mixing and chemical remediation may have unintended consequences on the fish population, and have not been trialled in this context.

It is possible to reintroduce fish to a site, post-extirpation, if the site conditions have become suitable (e.g. through reduced nutrient loading), or to relocate fish to sites with more suitable ecological conditions (Adams et al. 2014). If fish are relocated to a site with more suitable conditions, the impact of the threshold can be avoided (Winfield et al 2008, Waters et al., 2018). Adaptation approaches are summarised in Table 12.

*Table 12. Adaptation approaches for temperature on suitable habitat for rare fish species*

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Local nutrient management to prevent nutrients from entering the lake – this could include reducing run-off from agriculture and enhancing wastewater treatment. | Agri-environment schemes and rules for farmers are in place to reduce instances of agricultural nutrients running off into watercourses. Rules apply to those receiving funding under CAP pillar 1 and pillar 2 as well as those within nitrate vulnerable zones.<br><br>Nutrient management guides such as RB209 assist farmers in reducing pollution risks.<br><br>The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018 came into force in April 2018 (CCC 2019). Monitoring data is gathered by the Environment Agency. In Scotland this is controlled by the Water Environment (Diffuse Pollution) (Scotland) Regulations 2008 and | There has been an increase in the number of freshwater sites of specific scientific interest (SSSIs) in favourable condition but the proportion of surface water bodies in high or good ecological status, has reduced (CCC 2019). | **Delivering adaptation:**<br><br><u>Regulation</u>: Restricting the land use around lakes could help to prevent nutrients from entering the water. This could include buffer strips for agricultural production or withholding this land area for tree planting.<br><br><u>Advice</u>: Where farmers recognise the private benefits of precise nutrient management, information and advice can change behaviours and drive autonomous adaptation.<br><br><u>Incentives</u>: There are challenges internalising costs within a farm business as well as allocating costs as the source of numerous small pollution incidents are not easily identifiable. Therefore grants may be required to assist farmers with nutrient management. If land near | **Delivering adaptation:**<br><br>Implementing (or improving) nutrient management practices will have benefits within the next five years in terms of the amount of nutrients which reach watercourses. However, further adaptation such as land use change (buffer strips, afforestation etc.) may be required to have a greater impact. Combining these land management changes with water management practices (e.g. mixing and aeration) may be able to delay the threshold. Early action decreases water pollution and reduces the risk of lock-in; therefore timely action is important.<br><br>The new environmental land management schemes in the UK post-Brexit[8] will apply from 2023, |

[8] Environmental Land Management Scheme in England, the Sustainable Land Management Scheme in Wales, and the developing schemes in Scotland and Northern Ireland

| | | | | |
|---|---|---|---|---|
| | the Water Environment (Controlled Activities) (Scotland) Regulations 2011.<br><br>The National Environment Programme includes schemes to improve discharge from sewage (CCC 2019). This aims to reduce the risk of eutrophication and improve the quality of discharge water.<br><br>In England, the Water Environment Grant Scheme for improving the water environment (administered by the EA and Natural England, supported by EAFRD, and part of RDPE) was launched in 2018/19. | | the lake is to be taken out of agricultural production compensation may be required.<br><br>**Building capacity:**<br><br>There is huge scope for improving awareness of future climate change impacts and adaptation response associated with nutrients in watercourses. This needs to be targeted spatially and focused on the economic case as well as the public good aspect.<br><br>Land management techniques to limit the amount of nutrients which get in to watercourses are widely available (e.g. wastewater treatment, precision application of nutrients, buffer strips etc.). Capacity is therefore largely available, but action depends on the incentives or regulation in place. Increasing capacity may be required for actions | and are likely to include measures to reduce diffuse nutrient pollution. However, such adaptation options need to be clearly built into design and piloting [2019-2023]. Changes to regulation and advice provision are also being developed as part of Defra's 25YEP.<br><br>**Building capacity:**<br><br>Benefits can be realised within the next five years as small changes in land management can have a big impact on nutrient runoff which can then reduce algal blooms in watercourses. Building capacity in practices such as aeration, mixing and covering will provide additional options where nutrient management is not sufficient to prevent algal blooms, oxygen depletion, and subsequent loss of fish species. As there could be a long lead time in the development |
| Changing the conditions within the lake, for example through aeration or artificial mixing. | Not currently widely practiced. | N.A | | |

| | | | | |
|---|---|---|---|---|
| | | | related to aeration, mixing, and floating solar panels. | of these options, taking action sooner rather than later will result in options being available in a timelier manner. |

**Is risk managed by autonomous or planned adaptation?**

Planned adaptation will be required to manage the risk. In England, the risk from climate change is such that there may be no viable adaptation option. Adaptation benefits are largely for the public good, although there may be some private interest, for example for the water industry. Nutrient management can mitigate against the production of algal blooms and oxygen depletion; however, it is unlikely that all nutrients would be prevented from reaching watercourses. In these cases, water treatment options such as aeration and mixing can help to reduce the impact of algal blooms and improve oxygen conditions. However, there may be species in the water body which are unable to recover after the threshold has been crossed. If able to relocate species to more suitable sites, the impact of the threshold can be avoided. There are no current plans in place to address increasing water temperatures.

**Risks of lock-in**

Taking land out of production near the lake may create lock in

Potential loss of aquatic species if the threshold is crossed

Moving species out of the affected lake may create lock in

**Risk(s) interacting**

Water quality reduction if algal blooms increase and oxygen decreases, but increase in water quality possible through adaptation options

Biodiversity losses from oxygen depletion and habitat loss

| |
|---|
| Soil health will likely improve due to precision application of nutrients; there may also be reduced erosion risk due to buffer strips etc. |
| **Urgency scoring**<br><br>More urgent: more action needed – planned adaptation will be required to reduce the impact of the threshold, with implementation needed above levels already planned. Further research may be required for some mitigation measures which are not currently widely practiced (aeration, artificial mixing, etc.). |

**What is the impact of current levels of adaptation at mitigating these risks?**

Catchment-wide management of nitrogen and phosphorus diffuse sources and improved management of point sources, often domestic sewage can partly offset oxygen depletion. These are applied in nitrate vulnerable zones, but not widely elsewhere.

There has been an increase in the number of freshwater sites of specific scientific interest (SSSIs) in favourable condition, however more widely in the countryside, the number of surface water bodies in England in high or good ecological status has fallen since 2012 (CCC 2019). These figures can be used as an indication of the impact of adaptation (minimal), however factors beyond fish habitat volumes will be considered in these assessments so this is not a direct link to adaptation.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Management of nutrient sources and sediment loads can be applied to lakes supporting vendace populations to reduce impacts on oxygen depletion (excess phytoplankton growth) and spawning habitats (phytoplankton and sediment loads). Although not currently widely practiced, aeration, artificial mixing, and chemical remediation could be used to reduce oxygen depletion and promote fish habitat volumes, though an advanced assessment of the potential for unintended ecological consequences is highly recommended. If the threshold is crossed, and nutrients are not a limiting factor to algal blooms and oxygen depletion, water treatment options may be able to mitigate against the impact. If able to relocate fish species to more suitable sites, the impact of the threshold can be managed.

**In what scenarios are there limits to adaptation?**

The adaptation methods apply in most cases to the pre-conditions necessary for increases in plankton populations, oxygen depletion, and sediment loading from catchments, therefore they are to a large extent independent of the climate risk. However, the climate risk in areas known to have lakes that are otherwise suitable for vendace will dictate the number of water bodies that need to be considered for management. Lack of incentives or regulation may limit adoption of adaptation actions (e.g. nutrient management/buffer strips) by land owners, which would impact on the ability to prevent formation of algal blooms. There may be species in the water body which are unable to recover after the threshold has been crossed.

## 5.6 Temperature effects on zooplankton species composition in lakes

Figure 9 below summarises the threshold and assessment chain. Increased air temperatures lead to increased water temperatures. Above a monthly mean water temperature of 14 °C, changes in the composition of the zooplankton community occur. Changes at this trophic level cannot be easily translated into impacts on ecosystem services.

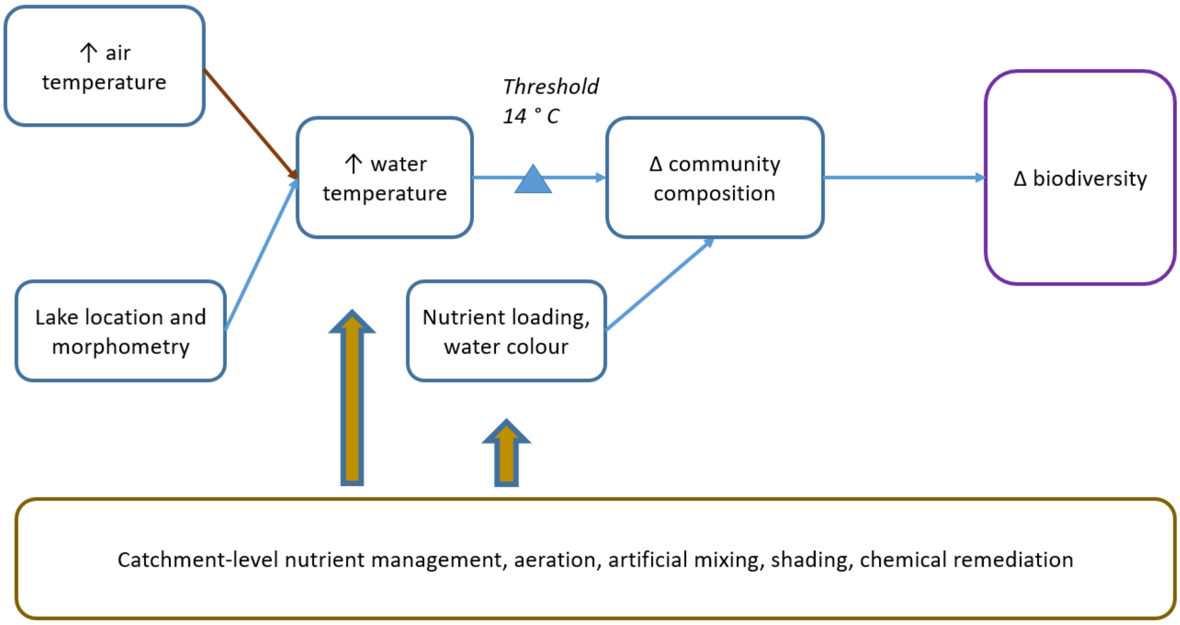


*Figure 9. **Impact chain for temperature effects on zooplankton species composition in lakes**. Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures.*

### 5.6.1 Justification of threshold used in the assessment

Increases in water temperature, because of rising air temperatures, can lead to changes in the species composition of the planktonic herbivore community (Bruel *et al* 2018). Warming water can stimulate the growth of filamentous phytoplankton, including cyanobacteria (Paerl & Huisman 2008), impacting upon food quality, and favouring different grazer species. Furthermore, warming may enhance fish predation on grazers, and change which species dominate the community (Gyllström *et al* 2005). Changing nutrient loading can interact with these effects by influencing the quantity and quality of food available to the grazers. A monthly mean water temperature threshold of 14°C was derived for impacts on zooplankton composition (Bruel *et al* 2018).

### 5.6.2 Impacts on natural assets and the services they provide

Changes in zooplankton community composition affect biodiversity, and have the potential to impact grazing pressure on phytoplankton, and thus water quality. Changes to the zooplankton community can also alter higher trophic levels in aquatic systems.

### 5.6.3 Ecosystem assessment – climate hazard thresholds

An empirical relationship between lake water temperature and air temperature was used to derive an air temperature threshold (see Supplementary Methods). Therefore, in this assessment the number of months with monthly mean air temperatures exceeding a 12.0 °C threshold was calculated. The air temperature differs from the water temperature threshold due to the higher specific heat capacity of water – see Appendix 1 for the equation.

Below we show the average number of months per year with mean water temperatures exceeding 14 °C for each scenario period (Table 13). All UK regions show an increase in the number of months exceeding the threshold in a warming world. Current levels of impact are already potentially substantial, with the threshold exceeded in all UK regions. Future projections suggest the level of impact will increase further. In England, the number of months exceeding the threshold increases from 3.7 at current day to 5.3 under a 4 °C scenario. In Wales the increase is from 3.3 at baseline to 4.9 under a 4 °C scenario. Scotland increases from 1.8 to 3.7 months exceeding the thresholds and Northern Ireland increases from 2.7 to 4.7 months under the 4 °C scenario. In all regions, current level of ecological risk is high, apart from in Scotland at current day, and all regions show a high level of risk under 4 °C. The consequences of changes in zooplankton communities on wider ecosystem services are difficult to assess.

*Table 13.* ***Average number of months per year where projected monthly mean water temperatures exceed a 14 °C threshold for 2003, at baseline and under 2°C and 4°C scenarios.*** *Data for 2003 shown for comparison with a previous 'hot year'.*

| | Number of months exceeding threshold | | | |
|---|---|---|---|---|
| **Region** | **2003** | **Baseline (2001-2010)** | **2 °C** | **4 °C** |
| North West England | 3 | 3.3 | 3.6 | 4.7 |
| North East England | 3 | 2.8 | 3.3 | 4 |
| Yorkshire and Humber | 3 | 3.3 | 3.6 | 4.8 |
| West Midlands | 3 | 3.4 | 4.1 | 5.1 |
| East Midlands | 3 | 3.6 | 4.1 | 5.3 |
| East of England | 4 | 4.2 | 4.5 | 5.8 |
| South West England | 4 | 3.8 | 4.3 | 5.6 |
| South East England | 4 | 4.4 | 4.5 | 5.9 |
| London | 4 | 4.6 | 4.9 | 6.7 |
| Wales | 3 | 3.3 | 3.7 | 4.9 |
| North Scotland | 2 | 1.2 | 1.9 | 3.3 |
| West Scotland | 3 | 2.4 | 3.2 | 4.1 |
| East Scotland | 2 | 1.8 | 2.4 | 3.8 |
| Northern Ireland | 3 | 2.7 | 3.6 | 4.7 |
| | | | | |
| England (average of regions) | 3.4 | 3.7 | 4.1 | 5.3 |
| Wales (average of regions) | 3.0 | 3.3 | 3.7 | 4.9 |
| Scotland (average of regions) | 2.3 | 1.8 | 2.5 | 3.7 |
| Northern Ireland (average of regions) | 3.0 | 2.7 | 3.6 | 4.7 |
| **UK (average of regions)** | **3.1** | **3.2** | **3.7** | **4.9** |

### 5.6.4 Economic assessment – impact on goods and services

It was not possible to calculate an economic assessment for impacts on zooplankton populations, due to difficulties in translating changes in the respective zooplankton community into an associated change in ecosystem service provision.

### 5.6.5 Adaptation

Climate-driven changes in community structure could offset the effects of restoration efforts.

Riparian planting to shade the edges of lakes provides a mechanism for reducing light and water temperature. Trees and shrubs reduce summer mean and maximum water temperatures, on average, by $2^oC$ to $3^oC$ in shaded areas of rivers and small water bodies (Woodland Trust, 2016). However this adaptation measure would not be feasible for the majority of lakes.

NAP actions include smarter targeting of fertiliser type and application in order to reduce the potential negative impact of agriculture on waterways. If nutrients are limited, the impact of increased temperature on algal blooms is lessened. Nutrients could be reduced through reducing run-off from agriculture through precision application, or by creating a buffer strip around fields and lakes to reduce loadings of pollutants reaching the water.

There is the potential for "top-down" management of zooplankton composition through fish biomanipulation to reduce predation on species that have an important role in mediating water quality, and to increase the availability of predation refuges for these species (Phillips *et al* 2015). Furthermore, continued vigilance regarding the potential for introduction of non-native predators of zooplankton (e.g. planktivorous fish like roach, Elliott *et al* 2015) is recommended. Adaptation approaches are summarised in Table 14.

*Table 14. Adaptation approaches for temperature impacts on zooplankton composition in lakes.*

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Local nutrient management to prevent nutrients from entering the lake – this could include reducing run-off from agriculture and enhancing wastewater treatment. | Rules apply to those receiving funding under CAP pillar 1 and pillar 2 as well as those within Nitrate Vulnerable Zones.<br><br>Nutrient management guides such as RB209 assist farmers in reducing pollution risks.<br><br>The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018 came into force in April 2018 (CCC 2019). Monitoring data is gathered by the Environment Agency. In Scotland this is controlled by the Water Environment (Diffuse Pollution) (Scotland) Regulations 2008 and the Water Environment (Controlled Activities) (Scotland) Regulations 2011.<br><br>The National Environment Programme includes schemes to improve discharge from sewage (CCC 2019). This aims to reduce the risk of | There has been an increase in the number of freshwater sites of specific scientific interest (SSSIs) in favourable condition but the proportion of surface water bodies in high or good ecological status, has reduced (CCC 2019). | **Delivering adaptation:**<br><br>Regulation: Restricting the land use around lakes could help to prevent nutrients from entering the water. This could include buffer strips for agricultural production or withholding this land area for tree planting.<br><br>Advice: Where farmers recognise the private benefits of precise nutrient management, information and advice can change behaviours and drive autonomous adaptation.<br><br>Incentives: There are challenges internalising costs within a farm business as well as allocating costs as the source of numerous small pollution incidents are not easily identifiable. Therefore grants may be required to assist farmers with nutrient management. If land near the lake is to be taken out of | **Delivering adaptation:**<br><br>Implementing (or improving) nutrient management practices will have benefits within the next 5 years in terms of the amount of nutrients which reach watercourses. However, further adaptation such as land use change (buffer strips, afforestation etc.) may be required to have a greater impact. Combining these land management changes with water management practices (e.g. mixing and aeration) may be able to delay the threshold. Early action decreases water pollution and reduces the risk of lock-in; therefore timely action is important.<br><br>The new environmental land management schemes in the |

| | | | | |
|---|---|---|---|---|
| | eutrophication and improve the quality of discharge water.<br><br>In England, the Water Environment Grant Scheme for improving the water environment (administered by the EA and Natural England, supported by EAFRD, and part of RDPE) was launched in 2018/19. | | agricultural production compensation may be required.<br><br>**Building capacity:**<br><br>There is huge scope for improving awareness of future climate change impacts and adaptation response associated with nutrients in watercourses. This needs to be targeted spatially and focused on the economic case as well as the public good aspect.<br><br>Land management techniques to limit the amount of nutrients which get in to watercourses are widely available (e.g. wastewater treatment, precision application of nutrients, buffer strips etc.). Capacity is therefore largely available, but action depends on the incentives or regulation in place. Increasing capacity may be required for actions related to aeration, mixing, and floating solar panels. | UK post-Brexit[9] will apply from 2023, and are likely to include measures to reduce diffuse nutrient pollution. However, such adaptation options need to be clearly built into design and piloting [2019-2023]. Changes to regulation and advice provision are also being developed as part of Defra's 25YEP.<br><br>**Building capacity:**<br><br>Small changes in land management can have a big impact on nutrient runoff which can then reduce nutrient loading in watercourses. Building capacity in practices such as aeration, mixing and covering will provide additional options where nutrient management is not sufficient to prevent nutrient loading, oxygen depletion, changes in community composition, and subsequent loss of |
| Changing the conditions within the lake, for example through aeration or artificial mixing. | Not currently widely practiced. | N.A | | |
| Shading the water to prevent warming, for example with surrounding trees or covering the lake, this could include solar panels on top of the lake. | Not widely practiced, although recent projects have been promoting tree and shrub planting along river banks to provide shading. | N.A. | | |

[9] Environmental Land Management Scheme in England, the Sustainable Land Management Scheme in Wales, and the developing schemes in Scotland and Northern Ireland

| | | | | |
|---|---|---|---|---|
| | | | | zooplankton species. As there could be a long lead time in the development of these options, taking action sooner rather than later will result in options being available in a timelier manner. |

**Is risk managed by autonomous or planned adaptation?**

Planned adaptation will be required to manage the risk. Adaptation benefits are largely for the public good, although there may be some private interest, for example for the water industry. Nutrient management can mitigate against the production of algal blooms and some changes in community composition; however, it is unlikely that all nutrients would be prevented from reaching watercourses. In these cases, water treatment options such as aeration and mixing can help to reduce the impact of nutrient loading. However, there may be species in the lake which are unable to recover after the threshold has been crossed.

**Risks of lock-in**

Taking land out of production near the lake may create lock in.

Potential loss of aquatic species if the threshold is crossed

**Risk(s) interacting**

Water quality reduction if algal blooms increase, but increase in water quality through adaptation options

Biodiversity losses from algal blooms

Soil health will likely improve due to precision application of nutrients; there may also be reduced erosion risk due to buffer strips etc.

**Urgency scoring**

More urgent: Research priority – further research is needed. Planned adaptation will be required, however, research may be needed to fill evidence gaps of how changes in zooplankton community affects the wider ecosystem. Further research may also be required for some mitigation measures which are not currently widely practiced (aeration, artificial mixing, shading etc.).

**What is the impact of current levels of adaptation at mitigating these risks?**

Catchment-wide management of nitrogen and phosphorus diffuse sources and improved management of point sources, often domestic sewage can partly offset oxygen depletion. These are applied in nitrate vulnerable zones, but not widely elsewhere.

The declining number of surface water bodies in good or high condition in England since 2012 suggests that current actions to maintain water quality by reducing catchment nutrient sources are not widespread enough to serve as adaptation for this pressure. It should be noted that WFD condition categories are not based solely on nutrient concentrations in water however.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Riparian planting to shade the edges of lakes provides a mechanism for reducing light and water temperature. Trees and shrubs reduce summer mean and maximum water temperatures, on average, by 2$^{o}$C to 3$^{o}$C in shaded areas of rivers and small water bodies (Woodland Trust, 2016). Therefore this adaptation measure can be used to reduce the risk from rising temperatures, although only in areas which are shaded, and may not be feasible for some lakes. Actions involving aeration, artificial mixing, and chemical remediation could also be used to reduce oxygen depletion.

**In what scenarios are there limits to adaptation?**

The adaptation methods apply in most cases to the pre-conditions necessary for increases in plankton populations and oxygen depletion, therefore they are to a large extent independent of the climate risk. However, the geographical pattern of climate risk will dictate the number of water bodies that need to be considered for management. Lack of incentives or regulation may limit adoption of adaptation actions (e.g. nutrient management/buffer strips) by land owners, which would impact on the ability to prevent formation of algal blooms. There may be species in the water body which are unable to recover after the threshold has been crossed. Where lakes are unsuitable for riparian planting to increase shade and lower water temperatures there may be limited options for adaptation.

# 6 Agricultural systems: Farmland and grasslands

## 6.1 Summary – Farmland and grasslands

Assessment of impacts on agricultural systems covers two Broad Habitat types as defined in the UK National Ecosystem Assessment: Enclosed farmland and Semi-natural grasslands, referred to as Farmland and Grasslands in the rest of this assessment.

The literature review identified five potential threshold-based impacts (section 16.2.1), of which four were taken forward in the national screening assessment. Three were related to temperature: increased parasite outbreaks in sheep, declines in milk production, and declines in wheat production, and one impact was related to rainfall: increased soil erosion. Additional impacts linked to flood risk were described, but not fully assessed in this project as they were the focus of a separate CCRA3 research project on flooding.  A case study focused in more detail on the losses to milk production.

*Temperature effects on lamb production (Ne 7, Ne 8)*

An increase in the number of days where daily mean temperature exceeds a 9 °C threshold allows sheep parasites to increase their life cycle more frequently, with health impacts for sheep and economic costs to farmers.

Overall, at a UK level, annual costs to farmers from parasite infection of lambs are projected to increase from £81 million per year at baseline to £97 million per year under a 2 °C scenario and £113 million per year under a 4 °C scenario.

Current adaptation measures focus on treatment of parasite infection. The NAP actions include managing existing animal diseases, and lowering the risk of new animal diseases. However, adaptation is not currently widely practiced, therefore, the impact of current levels of adaptation at mitigating these risks is low. Raising awareness of the risks and impacts of parasite infection is key as the adaptation response relies on the action of individual farmers.

**Urgency scoring** - More urgent: research priority - Further investi

gation is needed to gather evidence of risks and look at potential adaptation options.

*Temperature effects on milk production (Ne 7)*

Exceeding a temperature-humidity index (THI) of 74 leads to a decrease in milk production of 0.2 kg per cow per unit THI above the threshold, leading to economic losses for dairy farmers.

Overall, at a UK level, annual costs to farmers are projected to increase from £2.5 million per year at baseline to £3.8 million per year under a 2 °C scenario and £15.9 million per year under a 4 °C scenario.

There are no adaptation plans specific to the impact of heat stress on livestock within the current NAP. Current levels of adaptation are low as heat stress is not considered to be a major issue in the UK. However, milk producers are likely to pursue reactive adaptation to safeguard economic returns, but this could be very capital-intensive.

**Urgency scoring -** More urgent: more action needed - Action is needed to increase capability and put adaptions in place (e.g. through housing systems with adequate fans and sprinklers). Research into heat stress tolerant breeds could allow production to continue without extensive changes to husbandry.

*Temperature effects on wheat production (Ne 7)*

Exceeding a maximum daily temperature of 32 °C during anthesis (between May and mid-June) leads to reduced number of grains in wheat, and exceeding a maximum daily temperature of 35 °C for at least three consecutive days during the grain-filling period (from mid-June to end of July) results in reduced grain size. This leads to lower wheat yields and economic losses to farmers.

The anthesis threshold is effectively not exceeded in the UK under any scenario. The grain-filling threshold is exceeded under a 4 °C scenario, in four regions in England. The regional pattern of exceedance is important as these are key wheat producing areas. This results in lost wheat production totalling £42 million in the UK, which represents 2% of the total value of wheat production in 2018.

This is not currently a widespread issue in the UK, so adaptation actions are not yet in place. Further research on plant breeding and the availability of longer-season or heat-stress resistant varieties for widespread commercial use would avoid the impacts of exceeding the threshold. Awareness raising will also be important in high-risk areas to inform planting decisions in due course.

**Urgency scoring –** More urgent: Research priority.

*Rainfall effects on soil erosion (Ne 5, Ne 7)*

Exceedance of a threshold daily rainfall of 30 mm leads to increased soil erosion, taking account of additional risk factors (soil type, topography and land management). This leads to reduced soil fertility and reduced crop yields and economic losses to farmers.

Projected soil losses due heavy rainfall increase from 4.2 million tonnes at baseline, increasing by a factor of three to 14.3 million tonnes under a 2 °C scenario, but dropping slightly to 11 million tonnes under the 4 °C scenario due to reductions in intense rainfall in the areas with most arable production in the south and east of the UK.

Soil erosion leads to relatively low impacts on crop yield. Annual production losses amount to £5.5 million under a 2 °C scenario and £3.8 million under a 4 °C scenario. While economic losses are low, soil is a finite resource and erosion leads to an irreversible loss of natural capital. The impacts on a wider set of functions such as flooding and greenhouse gas emissions will greatly increase this cost estimate.

It is difficult to quantify the impact of the current levels of adaptation. Many farmers are improving their soil management, but soil erosion is an ongoing concern.

**Urgency scoring –** More urgent: More action needed - Early action would have benefits and build resilience as well as reduce the risk of lock-in. This would be a no and low regret adaptation since soil erosion results in substantial loss of natural capital.

## 6.2 Overview: Farmland and grasslands – national screening assessment

This section covers impacts on arable and livestock systems in both enclosed and unenclosed farmland and grasslands. Four of the five potential thresholds were taken forward in the national screening assessment. The impacts prioritised are shown in Table 15. The full list of potential impacts identified in the literature review can be found in Section 16.2.

*Table 15. **Potential threshold-driven impacts in farmland and grasslands.** Evidence for each of these thresholds is provided in the text below.*

| Climate-mediated stressor | Habitat | Threshold | Biophysical response | Societal end-point affected | Aligned risk descriptors |
|---|---|---|---|---|---|
| Temperature | Grassland | Daily mean temperature > 9 °C | Parasite outbreaks in sheep | Lamb production | Ne 7, Ne 8 |
| Temperature | Farmland/ Grassland | Temperature-Humidity Index, THI > 74 | Decrease in milk yield per cow | Milk production | Ne 7 |
| Temperature | Arable Farmland | Daily maximum temperature > 32 °C (from 1 May to 15 June) | Decrease in wheat productivity | Wheat production | Ne 7 |
| Rainfall | Farmland/ Grassland | Daily rainfall > 30 mm, in combination with RUSLE analysis for soil erosion potential | Soil erosion, loss of topsoil | Crop yield | Ne 5, Ne 7 |

## 6.3 Temperature effects on parasite outbreaks in livestock.

Figure 10 below summarises the threshold and assessment chain. A longer season above the developmental threshold of 9 °C daily mean temperature allows sheep parasites to more frequently complete their life cycle, causing disease and illness in sheep. This in turn results in weight loss of lambs and increased economic costs to farmers.

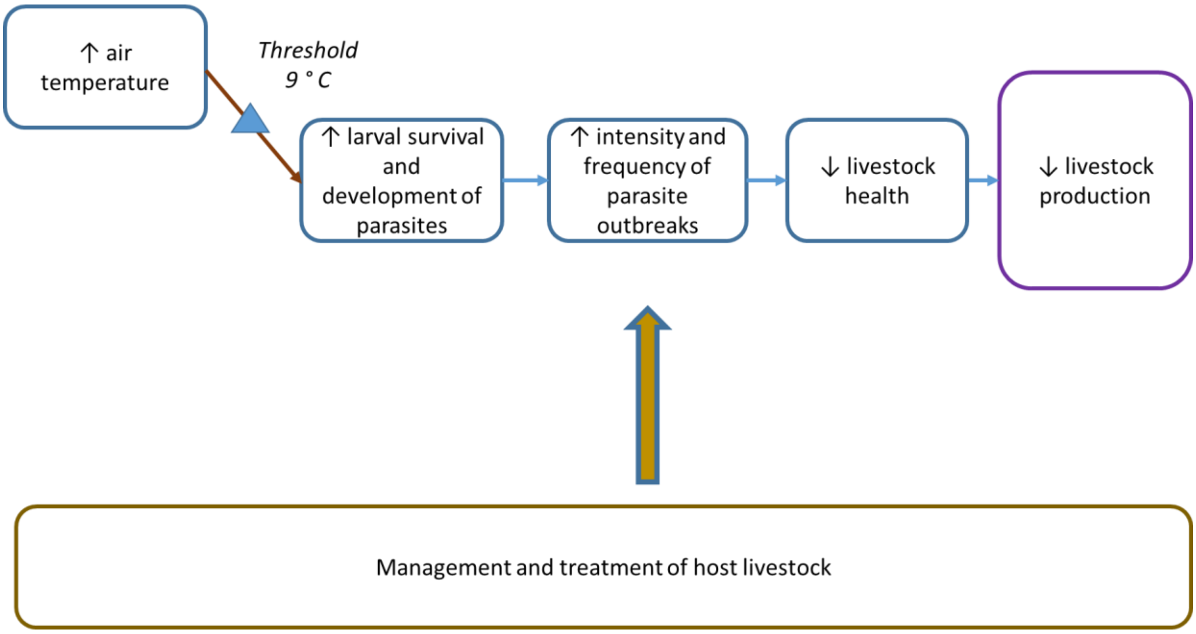


*Figure 10. **Impact chain for temperature effects on parasite outbreaks in sheep**. Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures.*

### 6.3.1 Justification of threshold used in the assessment

Exceedance of critical temperature thresholds for parasite development may cause non-linear increases in parasite outbreaks (Fox *et al.,* 2015). Incidences of *Fasciola hepatica* (liver fluke) affecting cattle and sheep farming have increasingly been reported throughout Europe, including the UK. The spread of this parasite and its associated diseases have also been linked to increasing temperatures under climate change (Caminade *et al.,* 2015). An important parasite is *Haemonchus contortus,* a parasitic nematode commonly linked to sheep farming, which has been the focus of several studies. These suggest that warmer winters allow it to more frequently complete its life cycle and have enabled a northward spread of its range into Wales and Scotland. Rose *et al.* (2015; 2016) modelled survival, development and infection of *Haemonchus contortus* in sheep. Although the full life-cycle is complex to model, a proxy threshold most relevant to the UK is the number of days above a daily mean temperature of 9 °C, which represents the development threshold for this parasite.

### 6.3.2 Impacts on natural assets and the services they provide

In parts of the UK where the climate allows the parasite can complete its life cycle within a year, this causes a plethora of diseases that negatively impact the welfare of grazing sheep and consequently the yield from sheep, and the economic viability of sheep farming (Short *et al.,* 2017).

### 6.3.3 Ecosystem assessment– climate hazard thresholds

For this analysis, the number of days with a daily mean temperature over 9 °C was calculated. Results of the climate risk are shown in Table 16. As an average across the UK, the development season for this parasite increases from 171 days in the baseline period by approximately 30 days under a 2 °C scenario, and 60 days under a 4 °C scenario. In England and Wales, the development season extends by a similar amount, starting from baselines of 179 days and 164 days respectively. In Scotland, the development season is much shorter at baseline, 127 days, but increases by a similar duration. In Northern Ireland, the development season increases from a baseline of 155 days by 40 days under a 2 °C scenario and 60 days under a 4 °C scenario.

*Table 16.* ***Number of days per year with daily mean temperature > 9 °C, by region. Average over ten year period for baseline (2001 – 2010), for 2 °C and 4 °C scenarios.***

| **Region** | **Baseline (2001-2010)** | **2 °C** | **4 °C** |
|---|---|---|---|
| North West England | 157 | 187 | 217 |
| North East England | 142 | 171 | 201 |
| Yorkshire and Humber | 162 | 188 | 220 |
| West Midlands | 176 | 204 | 237 |
| East Midlands | 179 | 204 | 237 |
| East of England | 192 | 217 | 253 |
| South West England | 194 | 222 | 258 |
| South East England | 197 | 222 | 260 |
| London | 213 | 233 | 270 |
| Wales | 165 | 197 | 228 |
| North Scotland | 116 | 150 | 178 |
| West Scotland | 142 | 174 | 203 |
| East Scotland | 124 | 155 | 183 |
| Northern Ireland | 156 | 196 | 215 |
| | | | |
| England (average of regions) | 179.2 | 205.5 | 239.2 |
| Wales | 164.6 | 197.2 | 227.9 |
| Scotland (average of regions) | 127.0 | 159.7 | 188.1 |
| Northern Ireland | 155.8 | 195.6 | 215.4 |
| | | | |
| **UK (average of regions)** | **165.3** | **194.4** | **225.7** |

### 6.3.4 Economic assessment – impact on goods and services

We estimate monetary losses from parasite infection by adapting findings from Nieuwhof and Bishop (2005) who calculated an £86 million loss per year to the Great Britain sheep industry in 2005. Nieuwhof and Bishop obtained this value using a bottom-up approach based on the costs of anti-helminthic treatment (medicine) and weight losses of lambs. We assume this represents the monetary total loss at baseline.

To estimate changes in parasite infection due to the temperature threshold effect, we assume that the number of days above 9 °C linearly increases the proportion/number of lambs infected. In addition, we assume a linear relationship between the number of lambs affected by infection and monetary losses (Nieuwhof and Bishop 2005).

To obtain the monetary losses from parasite infection at baseline in each region, we calculate the per-lamb monetary loss in Nieuhof and Bishop, and scale losses regionally using the lamb population in each region from the June 2017 Survey of Agriculture and Horticulture. Baseline economic losses using this approach total £81 million in 2017 which is similar to the value of £86 million estimated by from Nieuwhof and Bishop (2005).

For future years, we calculate the monetary loss in each region by estimating the percentage change in number of warm days under 2 °C and 4 °C scenarios from baseline (Table 16). These are shown in Table 17.

For the UK as a whole, at the baseline annual economic losses are already £81 m per year. This compares to the total production value of sheep meat in 2018 at £1.2 billion in the UK, around 7% of total production[10]. Under the 2 °C scenario, monetary losses increase to £97 m per year while under the 4 °C scenario they total £113 m per year. In England, losses increase from £37 m per year at baseline to £43 m and £50 m per year under 2 °C and 4 °C scenarios respectively. In Wales they increase from £22 m per year to £27 m and £31 m per year, while in Scotland annual losses increase from £16 m to £20 m and £23 m. In Northern Ireland they increase from £4.8 m to £6.1 m and £6.7 m per year. Projected economic costs of greater parasitic outbreak could thus cost up to 10% of the value of lamb production under a 4 °C scenario.

10 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/860944/agriaccounts-tiffstatsnotice-27jan20.pdf

*Table 17.* ***Annual economic losses in lamb production by region. Average over ten year period for baseline (2001 – 2010), 2 °C and 4 °C scenarios.***

| Region | Total no. lambs (million) | Monetary loss (£ million) | | |
|---|---|---|---|---|
| | | Baseline (2001-2010) | 2 °C | 4 °C |
| North West England | 1.6 | 7.4 | 8.9 | 10.2 |
| North East England | 1.1 | 5.0 | 6.0 | 7.0 |
| Yorkshire and Humber | 1.1 | 5.4 | 6.2 | 7.3 |
| West Midlands | 1.2 | 5.4 | 6.3 | 7.3 |
| East Midlands | 0.7 | 3.1 | 3.6 | 4.1 |
| East of England | 0.2 | 0.8 | 0.9 | 1.0 |
| South West England | 1.6 | 7.5 | 8.5 | 9.9 |
| South East England | 0.6 | 3.0 | 3.4 | 4.0 |
| London[1] | | | | |
| Wales | 4.9 | 23.0 | 27.4 | 31.8 |
| North Scotland[2] | - | - | - | - |
| West Scotland[2] | - | - | - | - |
| East Scotland[2] | - | - | - | - |
| Northern Ireland | 1.0 | 4.9 | 6.1 | 6.7 |
| | | | | |
| England (total) | 8.0 | 37.6 | 43.8 | 51.0 |
| Wales (total) | 4.9 | 23.0 | 27.4 | 31.8 |
| Scotland (total) | 3.4 | 16.0 | 20.1 | 23.7 |
| Northern Ireland (total) | 1.0 | 4.9 | 6.1 | 6.7 |
| **UK (total)** | **17.3** | **81.4** | **97.4** | **113.2** |

1 – London lambs data included in South East England; 2 – See Scotland total

### 6.3.5 Adaptation

Adaptation options include managing the grazing behaviour of host livestock to limit parasite spread, for example moving animals to 'safe' grazing areas, and using new resources and techniques to treat parasite infection. The timing of reproduction, housing and grazing could also be altered to try and reduce the risk of parasites, and mitigate against the threshold effect. Longer term adaptation after a threshold effect may include changing animal species or production systems where current practice is no longer viable. Another adaptation would be to breed resistance in host species. These adaptations could be something that decision makers should be looking at in order to determine whether these are possibilities for future production post-threshold.

New vaccinations may be another way of mitigating against the impact of the threshold. The cost of liver fluke in beef is estimated at £90 per calf (ADAS 2013). The cost of treating fluke in beef youngstock is £3/head (taking into account the cost of flukicide treatment, as well as the labour to administer this); therefore the cost benefit is £87 per calf (ADAS 2013). Similarly, the cost of fluke per lamb is estimated at £6 per lamb, with the cost of flukicide treatment and labour to administer this estimated as £0.44 per lamb; giving a net benefit of £5.60 (ADAS 2013). This demonstrates that using vaccinations can reduce the risk of economic losses due to increased spread of parasites. However, the cost benefit will vary based on whether a vaccination is available for the specific parasite, and how much this costs. If a vaccine for a particular parasite is available and 100% effective, the impact of the threshold can be avoided.

Where land is very susceptible to parasites such as liver fluke, it may be that decisions are made to conduct transformative adaptation, whereby the land is taken out of livestock production and instead use this for woodland or wetland as a means of carbon storage. Incentives could be provided to land owners/users to change the use and management of high-risk land though post-Brexit agri-environment schemes or payment for public goods.

The NAP actions include:

- Managing existing animal diseases; and
- Lowering the risk of new animal diseases.

Actions within this include using the Public Health England invasive vector surveillance programme to develop and update understanding of the status, distribution and abundance of potential vector species; and enhancing the cross-government contingency plan for dealing with invasive mosquitoes to cover other veterinary and medically important insect vectors. However, the main focus within NAP is on managing the risk of new invasive species. As such, the tools for livestock farmers to manage parasite infection relies on improved awareness and action by land managers alongside better models/forecasting/communication to the farm sector and innovations in disease treatment. Adaptation approaches are summarised in Table 18.

**What is the impact of current levels of adaptation at mitigating these risks?**

Widespread adaptation is not widely practiced, therefore, the impact of current levels of adaptation at mitigating these risks is low. Existing actions taken by farmers as part of commercial best practice will have some impact on mitigating the risks.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Managing existing diseases by rotating worming, moving animals to 'safe' grazing, and changing animal husbandry by altering timing of reproduction, housing and grazing are all management options that can be undertaken in advance. Research into the use of new vaccines to treat parasite infections could also be undertaken to reduce the risk of this threshold occurring and to help manage the impact. Breeding resistance in host species, or changing animal species or production system, could be ways of managing the impacts of the threshold after it has been crossed. Likewise, if a vaccine for a particular parasite is available and 100% effective, the impact of the threshold can be avoided.

**In what scenarios are there limits to adaptation?**

Where an area is very susceptible to parasites such as liver fluke, adaptation actions may not be able to mitigate the impacts of the threshold, and it may be that decisions are made to take the land out of livestock production. The response to adaptation will be highly variable between individual farms and there will not be a uniform response across a local area.

*Table 18.* ***Adaptation approaches to temperature impacts on parasites in sheep***.

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Managing existing animal diseases, e.g. rotating worming, moving animals to 'safe' grazing | Relies on commercial good practice, including effective use of disease prediction services (NADIS 2019). | N.A | **Delivering adaptation:**<br>Assuming capacity is available, the following steps can be taken to deliver adaptation:<br>Regulation: Some regulatory action can be taken to protect animal welfare.<br>Advice: Distribution of information on managing existing animal disease and techniques to reduce risk.<br>Incentives: Capital grants can incentivise housing which may help to reduce risk of parasites from grazing. Other changes in husbandry could also be incentivised to promote action. Incentives could be provided for high risk land to be used for afforestation or wetland creation<br><br>**Building capacity:**<br>There is huge scope for improving awareness of future climate impacts and adaptation responses available with regards to livestock parasites. Research into new vaccines and treatment options will increase the ability for reactive adaptation. Better | **Delivering adaptation:**<br>Providing the capacity is available (required for research/vaccines/breeding resistance) benefits may be seen from action taken in the short term, as husbandry practices/ knowledge around managing existing diseases can be implemented quickly.<br>The new environmental land management schemes in the UK post-Brexit will apply from 2023 but adaptation options need to be built into design and piloting [2019-2023]. Changes to regulation and advice provision are also being developed as part of the 25YEP. As such, action in the next 5 years to build CC adaptation to agriculture policy is a priority<br><br>**Building capacity:**<br>New vaccines and breeding resistance require forward planning so starting this process |
| Use of new resources and techniques to treat parasite infection, including new vaccines | Requires research into different methods that could be used to treat infection. The development of vaccines for endoparasites and ectoparasites are difficult to produce and are not yet available (Skuce *et al.,* 2013). | N.A | | |
| Changes in animal husbandry, such as altering timing of reproduction, housing and grazing | These are readily available methods to farmers, although housing may require additional investment. Housing can create difficulties as increasing the amount of time spent indoors can result in an increase of housing-associated parasites, whereas increased time outside can result in greater risks of pasture-borne parasites (Fox *et al.,* 2012; Skuce *et al.,* 2013) | N.A | | |
| Change animal species or production system | This may have wide impacts on the landscape of UK agriculture and diets. No evidence of changes of this nature to date. | N.A | | |

| | | | | |
|---|---|---|---|---|
| Breeding resistance in host species | Breeding for resistance to parasites is possible, however work is still on-going. Evidence from New Zealand sheep shows that improvements can be made over a 10 year period, with reduced treatments required (Fox *et al.,* 2012; Abbott *et al.,* 2012). | N.A | monitoring systems and forecasting would also reduce risk. Increased research and monitoring would build the capacity needed to deliver adaptation. Coordination will be required across the country in order for actions to be effective. | early will be beneficial in order to inform decision making, and to see benefits in a timely manner.<br>The ability to make changes using new resources and techniques may be a longer process. However, action taken sooner rather than later will allow for informed decision making. Action taken will need to be coordinated across the country for maximum impact. |

**Is risk managed by reactive or planned adaptation?**

Can be managed by reactive adaptation where farmers have the awareness and knowledge to use forecasting tools and make changes. However, there is a high risk of parasite outbreaks in livestock being seen as a chronic disease and accepted as a seasonal effect. Adaptation strategies such as new vaccinations and breeding resistance would require forward planning. If a vaccine for a particular parasite is available and 100% effective, the impact of the threshold can be avoided. Coordination across the country would be required for these actions to be effective. It should also be noted that for high impact diseases, isolation and control once detected is often carried out by Government.

**Risks of lock-in**

In the long term, parasites may restrict livestock breeds which can be reared in parts of the UK.

**Risk(s) interacting**

Housing large herds can concentrate risks to water and air pollution, as well as negatively impact on animal welfare. Conversely, housing large herds indoors can facilitate use of technical manure-management approaches which reduce both water and air pollution.

**Urgency scoring**

More urgent: Research priority. Further investigation is needed to gather evidence of risks and look at potential adaptation options.

## 6.4 Temperature effects on milk production

Figure 11 below summarises the threshold and assessment chain. Exceedance of the temperature humidity index (THI) threshold leads to declines in milk yield per cow, leading to decreased milk production and costs to farmers. This assessment is the subject of further analysis in a case study (section 11), which focuses on analysis of a wider set of climate projections.

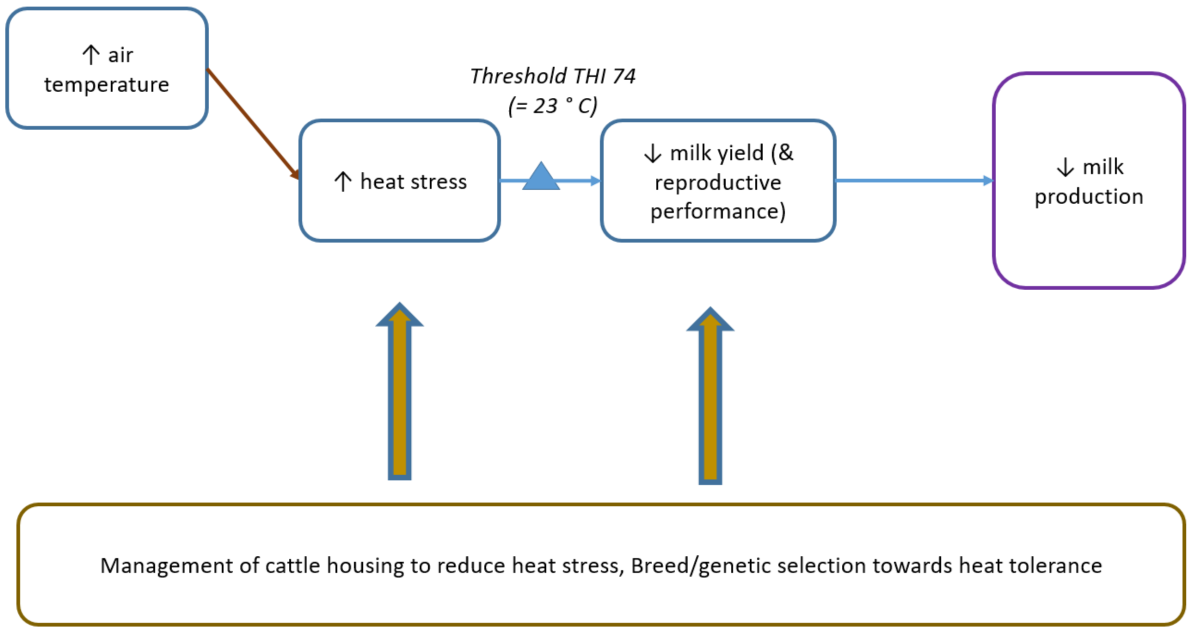


*Figure 11. **Impact chain for temperature effects on milk production**. Purple box shows endpoint social/economic impacts or impacts on biodiversity; Brown box shows potential adaptation measures.*

### 6.4.1 Justification of threshold used in the assessment

Heatwaves can create problems for a range of livestock systems, with the 2019 summer heatwave in the UK reportedly resulting in the death of thousands of intensively farmed chickens in one week alone (The Independent, 2019). On top of direct losses, heat stress can result in decreased milk production and reproductive performance in dairy herds.

Above a THI of 74, milk yield is reduced. Researchers cited in Dunn *et al.,* (2014) found that in the USA milk yield fell by between 0.2 kg/day and 0.9 kg/day for each point increase in THI. Studies cited within Mukherjee *et al.,* (2012) also report varying impacts, with daily milk loss per unit of THI stated as 0.25 litres (Argentina) and 0.29 +/- 0.04 kg (Sudan), and annual loss ranging from 31.4 +/- 12.2 kg of milk/cow (Netherlands), to 100-168 kg (USA) and 59 to 103 litres (Australia). In the UK, Dunn *et al.,* (2014) found that at least one herd in south-west England experienced a 30% reduction in milk yield during the 2006 heat wave. Using the A1B scenario from UKCP09, Dunn *et al.* (2014) predict that the number of days where THI exceeds the threshold for the on-set of mild heat stress could increase to over 20 days per year in southern parts of England by 2100.

The comfort threshold for dairy cows is above 72 THI and the 72 threshold can be breached at temperatures as low as 22°C if the relative humidity is high (around 90%) (Ohnstad, 2012). Effects will vary based on cow breed and size, however generally 72 to 79 THI results in mild heat stress, 80 to 90 results in moderate heat stress, and above 90 leads to severe heat stress (Polsky and von Keyserlingk, 2017). Researchers cited in Dunn *et al.* (2014) suggest that the THI for onset of heat stress in modern Holstein cattle could be as low as 65-69. Where the THI consistently exceeds 74 during the previous 4 days, milk production begins to decline (Linvill and Pardue, 1992; Polsky and von Keyerslingk, 2017). Mukherjee *et al.,* (2012) also found that THI has a significant nonlinear negative effect on milk production. Based on Polsky and von Keyserlingk, (2017) and Linvill and Pardue (1992) we apply a threshold THI of 74.

### 6.4.2 Impacts on natural assets and the services they provide

As well as reduced milk production, increased temperatures also result in a decrease in conception rates (Wolfenson and Roth, 2019). Higher temperature reduces the intensity and duration of oestrous expression, which negatively impacts on the cow's ability to display natural mating behaviour (Orihuela, 2000); while most dairy cows are artificially inseminated, there is still a reliance on identifying animals for breeding on the basis of behaviours. Media articles during the 2018 heatwave in the UK reported cows 'aborting' their calves due to the stress of the hot weather (BBC, 2018a) and 'not milking' as they should (BBC, 2018b).

The economic losses from heat stress can be substantial. In the US, annual economic losses range from $1.7 to $2.4 billion. Of this, nearly $900 million is specifically from the dairy industry, arising from decreased reproduction and milk production, alongside increased culling (St-Pierre *et al.,* 2003).

### 6.4.3 Ecosystem assessment – climate hazard thresholds

For this assessment, we use a decline in milk yield of 0.2 kg /day (Dunn et al. 2014) for each unit increase in THI above a threshold of 74, which equates to 23 °C. This is at the conservative end of the 0.2-0.9 kg/day range. The calculations underlying this threshold were as follows: The formula that Dunn *et al.,* (2014) use to calculate THI is: THI = (1.8T + 32) – (0.55 – 0.005RH) x (T – 26.8), where T = temperature (°C) and RH = relative humidity (%). The average relative humidity (RH) of a UK summer ranges from around 71% to 82% depending on location (Jenkins *et al.,* 2008). Average RH in winter ranges from 83% to 86% (Jenkins *et al.,* 2008). Using the Dunn *et al.,* (2014) calculation, and the summer relative humidity values from Jenkins *et al.,* (2008), THI reaches 74 at 23°C (at 71% RH) and 23.1°C (82% RH). For 82% RH, 26.7°C would induce moderate heat stress (THI of 80), and 32.7°C (at 82% RH) would lead to severe heat stress (THI of 90). The relationship between air temperature and THI is partly dependent on Relative Humidity, but not strongly so, and we assume a constant humidity value in this assessment (sensitivity analysis which varied the humidity by as much as 20% showed a change in the THI of less than 0.7 of a unit). For this assessment we calculate the number of days where daily maximum temperature exceeds 23 °C, the onset of mild heat stress, at an average summer relative humidity of 75%, (equivalent to a THI of 74 using the equation of Dunn et al. (2014)).

Hot-day temperatures already exceed the onset of mild heat stress in every UK region (Table 19), varying from 1 day per year in North Scotland up to as much as 32 days in London, and 14 days in some key milk-producing regions like South West England. Future maximum daily temperatures lie predominantly within the 'mild heat stress' range (Polsky and von Keyerslingk, 2017). Across the UK as a whole, the number of days exceeding the threshold increases from 11 at baseline to 15 days under a 2 °C scenario and more than triples to 36 days under a 4 °C scenario.

In England, the number of days exceeding the threshold increases from 16 days at baseline, to 21 days and 51 days. In Wales, it increases from 6.9 days at baseline to 8.8 days and increases four-fold to 27 days under a 4 °C scenario. In Scotland it increases from 1.6 days at baseline to 2.5 days and 7.6 days, while in Northern Ireland it increases from 2.6 days to 3.1 days and 10 days. The exceedance of temperature thresholds is important for the distribution of impacts in the UK given dairy production is mainly concentrated in England where with 1.1 million dairy cows, 61% of total UK dairy cows, are located. In Wales where there is also a significant increase in temperature exceedance there are 0.25 million dairy cows (13% UK total), along with a further 0.4 million in Northern Ireland (16% of UK total). In Scotland where incidence of temperature exceedance is projected to be lower, 0.2 million cows (10% of UK total) are located.

*Table 19. **Average number of days per year where the daily maximum temperature exceeds THI = 74 for baseline (2001 – 2010), 2 °C and 4 °C scenarios, by region**. Average of daily maximum temperature for the periods above the threshold, and the equivalent THI. All data are average over ten year period.*

| | Number of days exceeding threshold | | | Average temperature above threshold | | | THI equivalent | | |
|---|---|---|---|---|---|---|---|---|---|
| **Region** | Baseline (2001-2010) | 2 °C | 4 °C | Baseline (2001-2010) | 2 °C | 4 °C | Baseline (2001-2010) | 2 °C | 4 °C |
| North West England | 5.8 | 6.8 | 20.2 | 24.3 | 24.3 | 25.3 | 76.2 | 76.2 | 77.8 |
| North East England | 4.6 | 4.8 | 19.0 | 24.2 | 24.2 | 24.9 | 75.9 | 76.1 | 77.2 |
| Yorkshire and Humber | 10.2 | 12.4 | 36.4 | 24.4 | 24.5 | 25.4 | 76.3 | 76.5 | 78.0 |
| West Midlands | 15.9 | 21.0 | 52.1 | 24.7 | 24.9 | 26.0 | 76.8 | 77.1 | 79.0 |
| East Midlands | 18.2 | 23.6 | 56.0 | 24.9 | 24.8 | 26.1 | 77.1 | 77.0 | 79.0 |
| East of England | 21.8 | 30.9 | 68.2 | 24.9 | 25.1 | 26.2 | 77.2 | 77.4 | 79.3 |
| South West England | 14.2 | 19.9 | 53.3 | 24.5 | 24.8 | 25.8 | 76.6 | 77.0 | 78.5 |
| South East England | 20.6 | 30.0 | 69.2 | 24.9 | 25.1 | 26.1 | 77.2 | 77.5 | 79.2 |
| London | 32.3 | 46.4 | 84.5 | 25.3 | 25.4 | 26.6 | 77.8 | 78.0 | 80.0 |
| Wales | 6.9 | 8.8 | 27.7 | 24.3 | 24.5 | 25.3 | 76.2 | 76.6 | 77.8 |
| North Scotland | 1.0 | 3.0 | 5.4 | 23.4 | 25.4 | 24.5 | 74.8 | 78.0 | 76.4 |
| West Scotland | 2.0 | 2.3 | 8.4 | 23.8 | 23.9 | 24.5 | 75.3 | 75.5 | 76.6 |
| East Scotland | 1.8 | 2.2 | 9.1 | 23.4 | 24.3 | 24.5 | 74.8 | 76.3 | 76.5 |
| Northern Ireland | 2.5 | 3.1 | 13.0 | 23.9 | 23.8 | 24.6 | 75.5 | 75.4 | 76.7 |
| England (average of regions) | 16.0 | 21.8 | 51.0 | 24.7 | 24.8 | 25.8 | 76.8 | 77.0 | 78.7 |
| Wales | 6.9 | 8.8 | 27.7 | 24.3 | 24.5 | 25.3 | 76.2 | 76.6 | 77.8 |
| Scotland (average of regions) | 1.6 | 2.5 | 7.6 | 23.6 | 24.5 | 24.5 | 75.0 | 76.6 | 76.5 |
| Northern Ireland | 2.5 | 3.1 | 13.0 | 23.9 | 23.8 | 24.6 | 75.5 | 75.4 | 76.7 |
| **UK (average of regions)** | **11.3** | **15.4** | **37.3** | **24.4** | **24.7** | **25.4** | **76.3** | **76.8** | **78.0** |

### 6.4.4 Economic assessment – impact on goods and services

We estimate the monetary cost of lost milk production due to heat stress by obtaining data on number of dairy cows per region from the June 2017 Survey of Agriculture and Horticulture, conducted by Defra in England and the relevant government departments in Scotland, Wales and Northern Ireland. In line with Defra (2017), dairy cows are defined as "female dairy cows over 2 years old with offspring".

THI was converted to milk production losses per hot day by assuming milk is lost at the rate of 0.2 litres per cow per THI unit over 74[11] (Ravagnolo et al, 2000).

Total milk production losses per region were calculated by multiplying the milk loss per hot day by the number of hot days in each region to find regional losses per year.

The monetary value of production losses per year is calculated using a milk price of 29.6 pence per litre in 2017/18 from Defra Farm Accounts. The amount of milk produced in the UK was 14.7 billion litres in 2017/18 which amounted to £4.3 billion in production value.

The estimated annual losses in milk output due to threshold temperature exceedance are shown in Table 20. In total across the UK, estimated annual losses from reductions in milk production under the baseline scenario total £2.5 million annually. These increase to £3.8 million under a 2 $^{o}$C scenario and to £15.9 million per year under a 4 $^{o}$C scenario. England currently provides 90 % of UK milk production. Therefore, absolute losses are highest in England with annual losses of £2.2 million at baseline, rising to £3.3 million under a 2 $^{o}$C scenario and to £13.5 million under a 4 $^{o}$C scenario, with the South West particularly heavily affected with £6.1 million in losses per year. In Wales, losses increase from £225,000 at baseline to £340,000 and £15 million under 2 $^{o}$C and 4 $^{o}$C scenarios respectively, in Scotland, losses increase from £16,000 to £81,000 and £197,000, while in Northern Ireland they increase from £70,000 to £81,000 and £656,000 respectively.

[11] Applying a THI of 74, rather than 72 specified in Ravagnolo et al. (2000), see preceding section

*Table 20.* ***Annual loss in milk production (litres) and annual economic losses (£), for baseline (2001 – 2010), 2 °C and 4 °C scenarios by region****. Average over ten year period. – represents No Data. See notes below table.*

| Region | Dairy Breeding Herd/cow (millions) | Baseline (2001-2010) | | 2 °C | | 4 °C | |
|---|---|---|---|---|---|---|---|
| | | Milk Production Loss (millions of litres) | Monetary Loss (£ million) | Milk Production Loss (millions of llitres) | Monetary Loss (£ million) | Milk Production Loss (millions of litres) | Monetary Loss (£ million) |
| North West England | 0.3 | 0.7 | 0.2 | 0.8 | 0.2 | 4.2 | 1.3 |
| North East England | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | 0.2 | <0.1 |
| Yorkshire and Humber | <0.1 | 0.4 | 0.1 | 0.5 | 0.2 | 2.4 | 0.7 |
| West Midlands | 0.2 | 1.4 | 0.4 | 2.0 | 0.6 | 8.5 | 2.5 |
| East Midlands | 0.1 | 0.9 | 0.3 | 1.0 | 0.3 | 4.2 | 1.3 |
| East of England | <0.1 | 0.2 | 0.1 | 0.3 | 0.1 | 1.0 | 0.3 |
| South West England | 0.4 | 3.2 | 0.9 | 5.1 | 1.5 | 21.0 | 6.1 |
| South East England | 0.1 | 0.8 | 0.2 | 1.3 | 0.4 | 4.6 | 1.3 |
| London[1] | - | - | - | - | - | - | - |
| Wales | 0.3 | 0.8 | 0.2 | 1.1 | 0.3 | 5.3 | 1.6 |
| North Scotland[2] | - | - | - | - | - | - | - |
| West Scotland[2] | - | - | - | - | - | - | - |
| East Scotland[2] | - | - | - | - | - | - | - |
| Northern Ireland | 0.3 | 0.2 | 0.1 | 0.3 | 0.1 | 2.2 | 0.7 |
| | | | | | | | |
| England (total) | 1.1 | 7.6 | 2.3 | 11.3 | 3.3 | 46.0 | 13.5 |
| Wales (total) | 0.3 | 0.8 | 0.2 | 1.1 | 0.3 | 5.3 | 1.6 |
| Scotland (total) | 0.2 | 0.1 | <0.1 | 0.2 | 0.1 | 0.7 | 0.2 |
| Northern Ireland (total) | 0.3 | 0.2 | 0.1 | 0.3 | 0.1 | 2.2 | 0.7 |
| **UK (total)** | **1.9** | **8.7** | **2.6** | **13.0** | **3.8** | **54.0** | **16.0** |

1 – London cattle data included in South East England; 2 – See Scotland total

### 6.4.5 Adaptation

Management practices can be altered to reduce the risk of heat stress, including increasing water intake, moving feeding times to cooler periods, increasing the shade available, and decreasing activity and movement (Polsky and von Keyserlingk, 2017). Other management approaches include changing the system so that cows are housed all year-round, combined with the use of fans and sprinklers. Currently, only about 5% of UK dairy cattle are kept indoors all year round, although most are housed in the winter (Dunn *et al.,* 2014). There is a trend for dairy herds to increasingly be housed inside to support intensive systems and robotic milking, however adaptation of these systems, for example the introduction of fans and sprinklers, may be required.

Generally, indoor temperatures are 3-5°C higher than the external temperature in northern Europe; however, the relative humidity varies (Dunn *et al.,* 2014). Depending on the scale and sophistication of the housing system, cooling through fans and water sprinklers can reduce the THI inside compared to outside. However, techniques such as water sprinklers can increase the humidity, meaning that temperatures need to be further reduced in order for these to have positive impact. A study in the USA found that the addition of sprinklers and fans reduced the body temperature of the cow by 1.7°C, which resulted in a 0.79kg/day increase in yields over cows which were not exposed to fans or sprinklers (NADIS, 2016). Note that averaging effects on the temperature calculations in this study will smooth out spatial variation in temperatures. In reality, even within the same region, some farmers will be more exposed than others to rising temperature effects.

There are no adaptation plans specific to the impact of heat stress on livestock within the current NAP.

Outside of the NAP, adaption options include:

- Installing shade for grazing cattle, including tree plantations/agroforestry and roofed areas;
- Installing fans and sprinklers in dairy herd housing;
- Monitoring THI to inform farmers on when to house cattle based on likely impact on milk production; and
- Research on how different breeds/genetics are affected by THI

The adaptations listed would be a way of mitigating against the effect of temperature by reducing the amount of time that the cows are exposed to the heat. If the threshold is crossed, the impact on milk production can be better managed where these adaptations have been taken up. Beyond the threshold, management options make it possible for milk production to continue, although cows may need to be permanently housed with a heavy reliance on internal systems to cool the indoor environment. Adaptation approaches are summarised in Table 21.

*Table 21. Adaptation approaches to temperature impacts on milk production.*

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Year-round housing and fans combined with sprinklers. Increasing airflow over a cow has a dramatic effect on evaporative heat loss from the skin. The results of research from the USA suggest that airflows as low as 10 km/hour can reduce respiration rates in heat stressed animals by as much as 50% (Ohnstad, 2012; Mukherjee *et al.,* 2012). | Heat stress is not considered to be a major issue in the UK so there are no significant adaptations in place. However, recent (2018 and 2019) heatwaves have raised the profile of the challenges associated with heat stress.<br>Increasingly dairy herds are being housed year round to support intensive production systems and robotic milking – these offer some protection against heat but additional adaptation may be needed, e.g. fans combined with sprinklers.<br>AHDB (2015) provide management guidance to reduce heat stress, including providing access to shade, ensuring buildings are adequately ventilated, and wetting the heads and backs of housed cattle. | N/A | **Delivering adaptation:**<br>Assuming capacity is available, husbandry practices (such as housing livestock with fans and sprinklers) can be adopted to deliver adaptation.<br>Regulation: Some regulatory action can be taken to protect animal welfare.<br>Advice: Where farmers recognise the private benefits of avoiding heat stress, information and advice can change behaviours and drive effective reactive adaptation.<br>Incentives: Capital grants can incentivise infrastructure, such as housing and fans, or roofed areas and tree plantations for grazing cattle, to manage heat stress.<br><br>**Building capacity:** | **Delivering adaptation:**<br>There are likely to be benefits from adaptation to heat stress risk in dairy cows.<br>Adapting husbandry practices such as housing cattle can limit the impacts of increasing THI as it prevents the cattle from being exposed to the heat. If the threshold is increasingly exceeded in the next 5 years, already having these adaptations in place will greatly reduce the negative impact on milk yield.<br>Providing capacity is available, transitioning to different breeds or using genetic selection for heat tolerance will prevent the need for investment in infrastructure.<br>The new environmental land management schemes in the UK post-Brexit will apply from 2023 but adaptation options |
| Breed/genetic selection | Not relevant to date. Studies from abroad evidence a decline in milk production when THI exceeded a threshold of 74 (Boonkum and Duangjinda 2014). This was associated with Holstein genetics, which is the dominant breed in the UK. | N/A | | |

| | | | | |
|---|---|---|---|---|
| | | | Supporting research on how different breeds/genetics are affected by THI could build capacity and increase the ability to deliver adaptation. Sharing learnings following the recent heatwaves would also be beneficial in order to increase knowledge on the impact that husbandry practices can have on productivity during higher temperatures. | need to be built into design and piloting [2019-2023]. Changes to regulation and advice provision are also being developed as part of the 25YEP. As such, action in the next 5 years to build CC adaptation to agriculture policy is a priority.<br><br>**Building capacity:**<br>Shared learnings and increased knowledge will lead to increased reactive adaption through changing husbandry practices to best reduce heat stress. Acting now means that farmers will have the knowledge required to prevent a negative yield impact on milk from increased THI. Early research into breed and genetic selection will provide an indication as to whether this could be a viable adaptation option. It would be valuable to have this information before changing husbandry practices due to risk of lock-in of housing. |

| |
|---|
| **Is risk managed by reactive or planned adaptation?**<br>Milk producers are likely to pursue reactive adaptation to safeguard economic returns but this could be very capital-intensive, especially if a housing approach is adopted. At the margins of heat stress, there are likely to be production and animal welfare risks and information and advice will be important to anticipate and minimise. The risk to production can largely be overcome if animals are kept in controlled conditions (e.g. housed); however there are longer term considerations of this, such as lock-in, animal welfare, and increased pollution. |
| **Risks of lock-in**<br>Investment in housed systems does risk lock-in. |
| **Risk(s) interacting**<br>Housing large dairy herds can concentrate risks to water and air pollution, but can also facilitate technical manure management solutions to reduce both water and air pollution compared with animals outside.<br>Animal welfare of housing large herds. |
| **Urgency scoring**<br>More urgent: more action needed - More action is required to increase capability and put adaptions in place (e.g. through housing systems with adequate fans and sprinklers) to prevent negative impacts of reaching threshold. These adaptations will allow production to continue in a different format after the threshold; likewise research into heat stress tolerant breeds would provide an option for production to continue without extensive changes to husbandry practices. |

**What is the impact of current levels of adaptation at mitigating these risks?**

Current levels of adaptation are low as heat stress is not considered to be a major issue in the UK; therefore the impact of adaptation is low. Guidance is provided by organisations such as AHDB on how to reduce heat stress in livestock. With heat stress becoming more apparent in recent years, increasing adaptation may be seen in future years. In theory, basic adaptation actions such as providing access to shade and building ventilation should be reasonably effective at mitigating the risks of heat stress.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Installing shade for grazing cattle, installing fans and sprinklers in dairy herd housing, and research on how different breeds are affected by THI could all be undertaken in advance to reduce the risk of the THI threshold being crossed. The impact on milk production once the threshold has been crossed will be lessened where these actions have been taken up. Such management options make it possible for milk production to continue, however, this could cause lock-in as cows may need to be permanently housed with a heavy reliance on internal systems to cool the indoor environment. This need for infrastructure can be avoided if there is a transition to different breeds, or using genetic selection for heat tolerance.

**In what scenarios are there limits to adaptation?**

Small scale farmers may not be economically equipped for adaptation where a capital-intensive housing approach is adopted.

## 6.5 Temperature effects on wheat production

Figure 12 below summarises the threshold and assessment chain. Exceedance of the temperature thresholds leads to reduced floret fertility and reduced grain filling, resulting in decreased wheat production and costs to farmers.

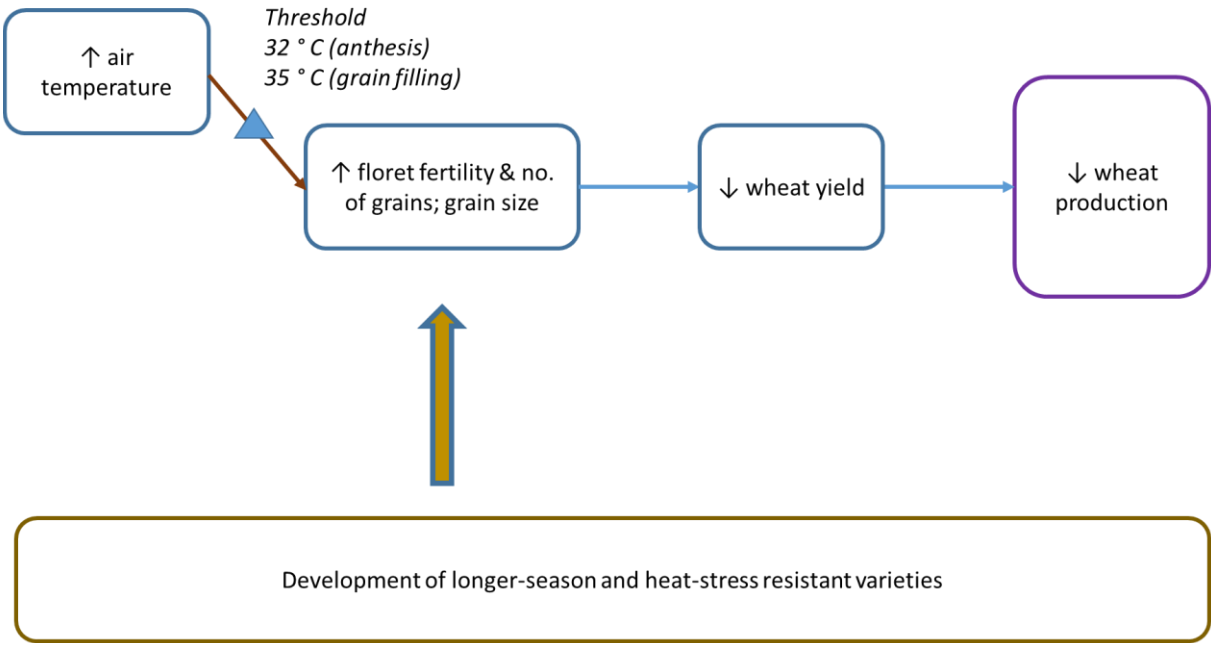


*Figure 12. **Impact chain for temperature effects on wheat production**. Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures.*

### 6.5.1 Justification of threshold used in the assessment

Specified temperature thresholds are described for different growth stages. Temperatures above 30 °C at the time of anthesis can reduce floret fertility and therefore reduce the number of grains which are developed (Stratonovitch and Semenov, 2015). Additionally, temperatures above 34 °C impact on grain yield through accelerating leaf senescence; this early senescence reduces the amount of light which is intercepted by the crop, thereby shortening the length of time associated with grain filling (Wardlaw and Moncur, 1995). This early senescence can also be driven by drought stress (Semenov *et al.,* 2014). At early grain filling, temperatures above 35 °C also limit the grain weight through affecting the development of the endosperm (Hawker and Jenner, 1993).

Rebetzke (Not Dated) found that maximum daily temperatures of 32 to 34 °C during flowering and grain filling led to a 10% yield reduction per day of elevated temperature, 34 to 36 °C led to a 20% yield reduction per day, and temperatures over 36°C led to a 30% yield reduction per day. Studies in China found that just a single day exposed to increased temperatures in the 20 days before anthesis resulted in a significant reduction of grain numbers. This was based on maximum daily temperature exceeding 32 °C (Yang *et al.,* 2017). Based on this evidence, we use a threshold of 32 °C for impacts on anthesis (reproductive development in the flower, leading to negative effects on grain numbers).

After anthesis, three consecutive days with maximum daily temperature above 35 $^{o}$C reduced yield during the grain filling period (Yang *et al.,* 2017). Change in water availability was not an issue in this study as the majority of grain is irrigated in China (Yang *et al.,* 2017). Hlavacova (2017) concluded from a European study that the magnitude of heat stress at anthesis has more impact on yield than the duration for which the crop is exposed to higher temperatures, although plants exposed to high temperatures for seven days did have lower grain numbers than those exposed to higher temperatures for three days. These experiments were conducted in growth chambers under four temperature regimes and the plants were watered every second day. Based on this evidence, we use a threshold of 35 $^{o}$C for impacts on grain filling.

As anthesis typically occurs between May and June in the UK (AHDB 2018), these months were used for the calculation of temperature thresholds. In the 20 days leading up to anthesis (May and early June), if there is one day where maximum daily temperatures exceed 32 $^{o}$C, this will impact grain numbers (Rebetzke, Not Dated). From June into July, three consecutive days with maximum daily temperature above 35 $^{o}$C could have the potential to impact on grain filling (Hawker and Jenner, 1993; Yang et al., 2017).

### 6.5.2 Impacts on natural assets and the services they provide

Wheat crops are highly sensitive to temperature changes, with advances in wheat genetics over previous years already being partly offset by changes in the European climate (Stratonovitch and Semenov 2015). Therefore realising increases in yield potential is becoming more difficult in view of changes in local weather patterns, including temperature and rainfall effects, which creates a challenge for feeding the increasing population.

Wheat is particularly sensitive to both extreme hot and cold temperatures in the reproductive stage, although the magnitude of the effect will vary with cultivar. Temperature rises could increase the number of occasions where anthesis coincides with high temperatures and water deficiency, as well as accelerating plant development such that anthesis could coincide with late frosts (Stratonovitch and Semenov, 2015).

### 6.5.3 Ecosystem assessment – climate hazard thresholds

Therefore, the climate risk was calculated as follows. For anthesis, the number of days where maximum daily temperature > 32 $^{o}$C from May to mid-June. For grain filling, the cumulative number of days where maximum daily temperature > 35 $^{o}$C for at least three consecutive days, from mid-June to end of July.

For the anthesis threshold, the climate models show no exceedance at baseline and only exceedance for 2 days in total over a decade for one region (London) under the 2 $^{o}$C scenario, with no exceedance under the 4 $^{o}$C scenario (data not presented in table form). This is not entirely surprising as these are temperatures in May and early June.

For the grain-filling threshold, the climate models show no exceedance at baseline conditions or under a 2 $^{o}$C scenario. However, under a 4 $^{o}$C scenario, the threshold is exceeded for around 3 to 8 days per decade in parts of central and southern England (Table 22). In the regions where exceedances do occur, the threshold is only exceeded once or twice per decade.

The regional concentration of these thresholds in central, eastern and southern England is significant given that significant amounts of production are in these areas. The East Midlands produces 20% of total wheat in the UK, with the South East contributing a further 13% to production, followed by production in the West Midlands adding another 10%[12].

*Table 22.* ***Number of days per year (averaged over a decade) when daily maximum temperature exceeds the grain-filling threshold, at baseline (2001-2010) and under 2 °C and 4 °C scenarios****. Calculated for periods where threshold is exceeded for at least three consecutive days (number of episodes per decade in brackets)*

| **Region** | **Baseline (2001-2010)** | **2 °C** | **4 °C** |
|---|---|---|---|
| North West England | 0 | 0 | 0 |
| North East England | 0 | 0 | 0 |
| Yorkshire and Humber | 0 | 0 | 0 |
| West Midlands | 0 | 0 | 0.3 (1) |
| East Midlands | 0 | 0 | 0.3 (1) |
| East of England | 0 | 0 | 0 |
| South West England | 0 | 0 | 0 |
| South East England | 0 | 0 | 0.3 (2) |
| London | 0 | 0 | 0.8 (1) |
| Wales | 0 | 0 | 0 |
| North Scotland | 0 | 0 | 0 |
| West Scotland | 0 | 0 | 0 |
| East Scotland | 0 | 0 | 0 |
| Northern Ireland | 0 | 0 | 0 |
| | | | |
| England average | 0.0 | 0.0 | 0.2 |
| Wales average | 0.0 | 0.0 | 0.0 |
| Scotland average | 0.0 | 0.0 | 0.0 |
| Northern Ireland average | 0.0 | 0.0 | 0.0 |
| **UK average** | **0.0** | **0.0** | **0.1** |

### 6.5.4 Economic assessment – impact on goods and services

To calculate the production of wheat per region, we obtained total wheat production and land area used for growing winter wheat in the UK from the June 2017 Survey of Agriculture and Horticulture. The land area for spring wheat is extremely small so we excluded this from the analysis. We broke this down by region by assuming that regions had the same yield of 7.8 tonnes/hectare[13] given that these areas share similar agro-climatic conditions and that UK wheat yields have remained largely constant over the past 20 years[14]. Following this, we multiplied wheat yield by the land area used for

[12] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/850569/regionalstatistics_overview_06dec19.pdf

[13] This assumption is taken from Defra Farm Statistics June 2018 based on UK wheat yields estimated for the 2018 season

[14] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/747210/structure-jun2018prov-UK-11oct18.pdf

growing winter wheat in each region to calculate regional production. A wheat price of £141 per tonne was taken from DEFRA Farm Accounts 2017/18, which is close to the 10 year average price of £148 per tonne for producer wheat prices in the UK according to the FAO.

In 2018, UK wheat production was 13.5 million tonnes, which translates to a total value of approximately £1.9 billion in gross revenue.

Since thresholds were not exceeded for the anthesis period, we focus the assessment on the grain filling period, using the threshold of 35 °C (Hawker and Jenner, 1993). Estimated yield losses were based on a loss of 20% for each day above the threshold (Rebetzke, Not Dated) for the daily maximum temperature band of 34 to 36 °C. Daily maximum temperatures did not reach 37 °C or higher.

Annual wheat losses per region were calculated under 2 °C and 4 °C scenarios based on the number of instances of threshold exceedance. These are shown in Table 23. Losses due to temperature threshold exceedance are not expected to occur under a 2 °C scenario. Losses under a 4 °C scenario do occur, but only once or at most twice per decade, in certain regions. However, losses may be high, with estimates up to £12 million a year for South East England and £19 million a year for East Midlands for a single event. Per year, these losses total £42 million for England under a 4 °C scenario.

*Table 23.* ***Average wheat losses per year for baseline (2001-2010), 2 °C and 4 °C scenarios.***

| | Baseline | | 2°C | | 4°C | |
|---|---|---|---|---|---|---|
| **Region** | **Production Loss ( thousands of tonnes)** | **Monetary Loss (£ million)** | **Production Loss (thousands of tonnes)** | **Monetary Loss (£ million)** | **Production loss (thousands of tonnes)** | **Monetary Loss (£ million)** |
| North West England | 0 | 0 | 0 | 0 | 0 | 0 |
| North East England | 0 | 0 | 0 | 0 | 0 | 0 |
| Yorkshire and Humber | 0 | 0 | 0 | 0 | 0 | 0 |
| West Midlands | 0 | 0 | 0 | 0 | 70 | 10.0 |
| East Midlands | 0 | 0 | 0 | 0 | 137 | 19.3 |
| East of England | 0 | 0 | 0 | 0 | 0 | 0 |
| South West England | 0 | 0 | 0 | 0 | 0 | 0 |
| South East England | 0 | 0 | 0 | 0 | 90 | 12.7 |
| London | 0 | 0 | 0 | 0 | 2 | 0.3 |
| Wales | 0 | 0 | 0 | 0 | 0 | 0 |
| North Scotland | 0 | 0 | 0 | 0 | 0 | 0 |
| West Scotland | 0 | 0 | 0 | 0 | 0 | 0 |
| East Scotland | 0 | 0 | 0 | 0 | 0 | 0 |
| Northern Ireland | 0 | 0 | 0 | 0 | 0 | 0 |
| England total | 0 | 0 | 0 | 0 | 300 | 42.2 |
| Wales total | 0 | 0 | 0 | 0 | 0 | 0 |
| Scotland total | 0 | 0 | 0 | 0 | 0 | 0 |
| Northern Ireland total | 0 | 0 | 0 | 0 | 0 | 0 |
| **UK total** | **0** | **0** | **0** | **0** | **300** | **42.2** |

### 6.5.5 Adaptation

Adaptation through escape (i.e. using different varieties to avoid the period when heat stress is greatest) is more widely practiced than adaptation through tolerance of the heat stress, in part due to the wide range of genes and alleles which influence the developmental rate (Semenov *et al.,* 2014). Reactive adaptation can also be implemented by amending sowing dates to avoid the highest temperatures occurring at sensitive growth stages.

Stratonovitch and Semenov (2015) state that a heat-tolerance trait will likely be critical in order to achieve high yield potential in southern and central Europe. If longer-season or heat-stress resistant varieties, which maintain similar or higher yields than current varieties, are available for widespread commercial use, the impact of the threshold exceedance can be avoided. This suggests the need for early investment in R&D by the plant breeding companies. The UK would benefit from research to identify heat stress tolerant varieties suited to the climate as well as further research on the impact of stress events on yield at different growth stages. As longer-term adaptation relies upon varietal development, early intervention would allow farmers to access commercial varieties in time for future climate events.

No actions specific to the impact of heat stress on wheat productivity are recorded in the current NAP. Approaches to adaptation are summarised in Table 24.

**What is the impact of current levels of adaptation at mitigating these risks?**

This is not currently a widespread issue in the UK, so adaptation actions are not widely in place. Defra has awarded £5.5 million of funding to four Crop Genetic Improvement Networks between 2018 and 2023; this includes the Wheat Genetic Improvement Network (WGIN). The aim of this funding is to improve the productivity and resilience of the arable sector (including field vegetables)[15].

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Amending sowing dates can reduce the risk of this threshold occurring; however, this decision by farmers would be dependent on a range of other factors, such as weather, rotation, yield impact and workforce availability, in addition to this threshold, which may not be the priority. Further research on plant breeding and the availability of longer-season or heat-stress resistant varieties for widespread commercial use would better insulate against the impact of the threshold.

**In what scenarios are there limits to adaptation?**

Reactive adaptation in the form of changing sowing dates may not be possible where farmers cannot access land at certain times of year (e.g. flooding/weather conditions), or where other factors (such as workforce availability etc.) limit the timing at which sowing can occur.

[15] http://www.wgin.org.uk/about/GINs.php

*Table 24.* ***Adaptation approaches to temperature effects on wheat production***.

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Longer-season wheat varieties and varieties with increased heat-stress resistance | Not currently an issue in the UK but research from other countries is relevant to future climate. Wang *et al.*, (2015) studied wheat flowering date in eastern Australia. They found that the flowering time of wheat is strongly controlled by temperature and is potentially highly sensitive to climate change. As a result of phenological responses to increasing temperatures, current wheat varieties may not be suitable for future climate conditions. Defra has awarded £5.5 million of funding to four Crop Genetic Improvement Networks between 2018 and 2023; this includes the Wheat Genetic | N.A | **Delivering adaptation:**<br>Regulation: N/A<br>Advice: Where farmers recognise the private benefits of using heat tolerant varieties, or changing planting times, information and advice can change behaviours and drive effective reactive adaptation.<br>Incentives: Research funding can incentivise research into plant breeding of heat resistant varieties.<br><br>**Building capacity:**<br>Scope for improving awareness of future climate impacts and adaptation responses available in the agriculture sector.<br>Further research on the impact of stress events at different growth stages on yield as well as research to identify heat-stress resistant varieties. | **Delivering adaptation:**<br>Given the research lead time to develop longer season/heat-stress resistant varieties, action should be taken sooner rather than later.<br>Changes to advice provision are also being developed as part of the 25YEP. As such, action in the next 5 years to build CC adaptation to agriculture policy is a priority.<br><br>**Building capacity:**<br>Early research in plant breeding may be important for the wheat crop in order to provide farmers with an alternative and prevent yield losses. If the threshold is reached, having longer-season or heat-stress resistant varieties available will be beneficial to reduce yield losses. The time taken to develop a new variety will influence the benefits seen within the next 5 years; therefore the sooner this process is started, the sooner benefits will be seen. |

| | | | | |
|---|---|---|---|---|
| | Improvement Network (WGIN). The aim of this funding is to improve the productivity and resilience of the arable sector (including field vegetables[15]. | | | |

| |
|---|
| **Is risk managed by reactive or planned adaptation?**<br>Growers will respond through reactive adaptation but research needs to be conducted well in advance of uptake, so an element of planned adaptation is necessary. If longer-season or heat-stress resistant varieties, which maintain similar or higher yields than current varieties, are available for widespread commercial use, the impact of the threshold can be avoided. |
| **Risks of lock-in**<br>N/A |
| **Risk(s) interacting**<br>There may be impacts on businesses associated with agricultural production |
| **Urgency scoring**<br>More urgent: Research priority – new varieties may be required to overcome threshold effects; this will benefit from early research in this area. |

## 6.6 Rainfall effects on soil erosion.

Figure 13 below summarises the threshold and assessment chain. Exceedance of the rainfall threshold leads to increased soil erosion, particularly in areas where topographic and other controlling factors lead to high erosion risk. Loss of soil leads to decreased soil fertility and therefore reduced crop yield and economic losses to the farmer.

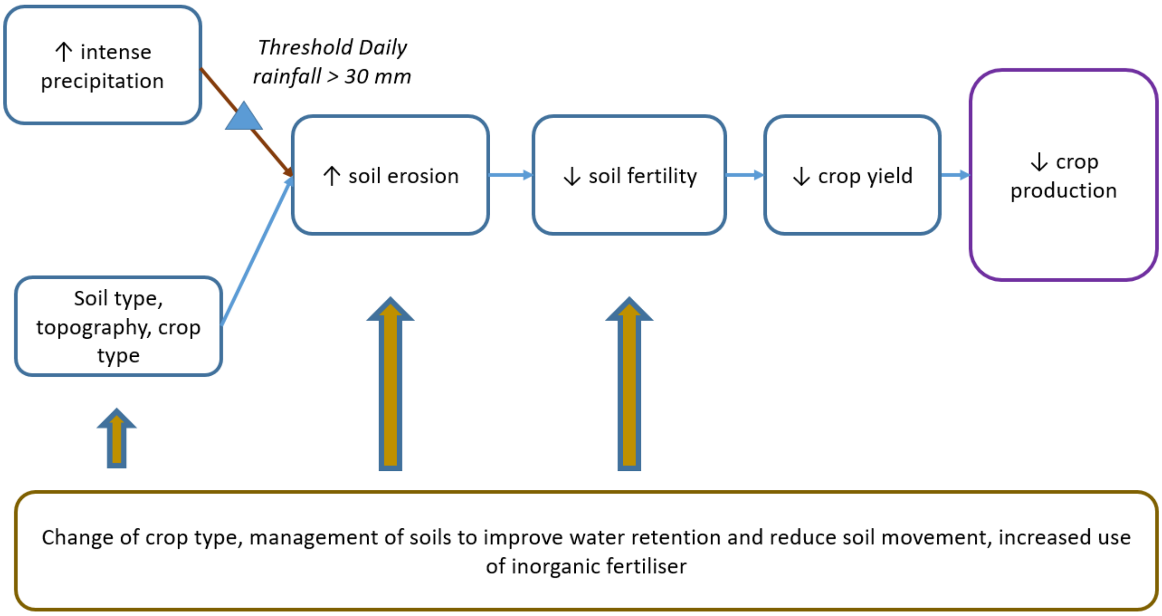


*Figure 13. **Impact chain for rainfall effects on soil erosion.** Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures.*

### 6.6.1 Justification of threshold used in the assessment

Rainfall intensity is the main climate variable considered to increase risk of soil erosion, although increased wind speeds also play a role and recent research suggests that prolonged periods of rainfall are also important. Projections of rainfall increases under climate change have been linked to increased rates of soil erosion. A study by Favis-Mortlock and Boardman (1995) suggested that a 7% increase in precipitation could cause a 25% increase in soil erosion in the South-East of England. Soil organic matter and soil structure influence water retention; with reduced water retention being a leading factor in soil erosion (Jones, *et al.,* 2009).

Soil erosion due to rainfall intensity is highly variable and is partly governed by interactions among land management regimes and climate. An increase in tilling due to changes in crop type combined with increased rainfall intensity can lead to substantial increases in soil erosion; without tilling, an increase in rainfall could lead to small increases, or large decreases in soil erosion. The timing of rainfall can also play a part. Non-linear increases in soil erosion have the potential to occur in years where intense rainfall occurs closely after tilling (Mullan *et al.,* 2012). The risk of soil erosion is highly dependent on crop type, land management practices as well as underlying climatic, edaphic and topographical factors. These factors often interact, with particular crops grown on specific soil types. The influence of climate change on the risk of soil erosion is complex and requires further research

(Brown *et al.,* 2016). In our analysis, a threshold value for heavy rainfall was defined as daily rainfall greater than 30 mm.

### 6.6.2 Impacts on natural assets and the services they provide

Increased soil erosion reduces the economic and environmental services soils provide (e.g. including carbon sequestration; water purification; and nutrient cycling) through the removal of valuable top soils. Increased intensity of rainfall events at times where soils are not adequately protected (e.g. just after tilling when there is no crop cover) could result in soil loss to the point where the land loses its productive capacity, and therefore reductions in crop yield.

### 6.6.3 Ecosystem assessment – climate hazard thresholds

High risk of soil erosion results from a combination of rainfall intensity, soil type and crop type. For this regional assessment, we focus on change in rainfall intensity in combination with the potential for soil erosion. The data source for erosion potential was the 2015 RUSLE map of soil erosion produced for Europe at 100m resolution (Figure 14) (Panagos et al. 2015). This shows which parts of the UK currently experience high levels of soil erosion, and takes into account the potential for erosion (primarily governed by soil type, topography and land cover/land use) as well as rainfall intensity.

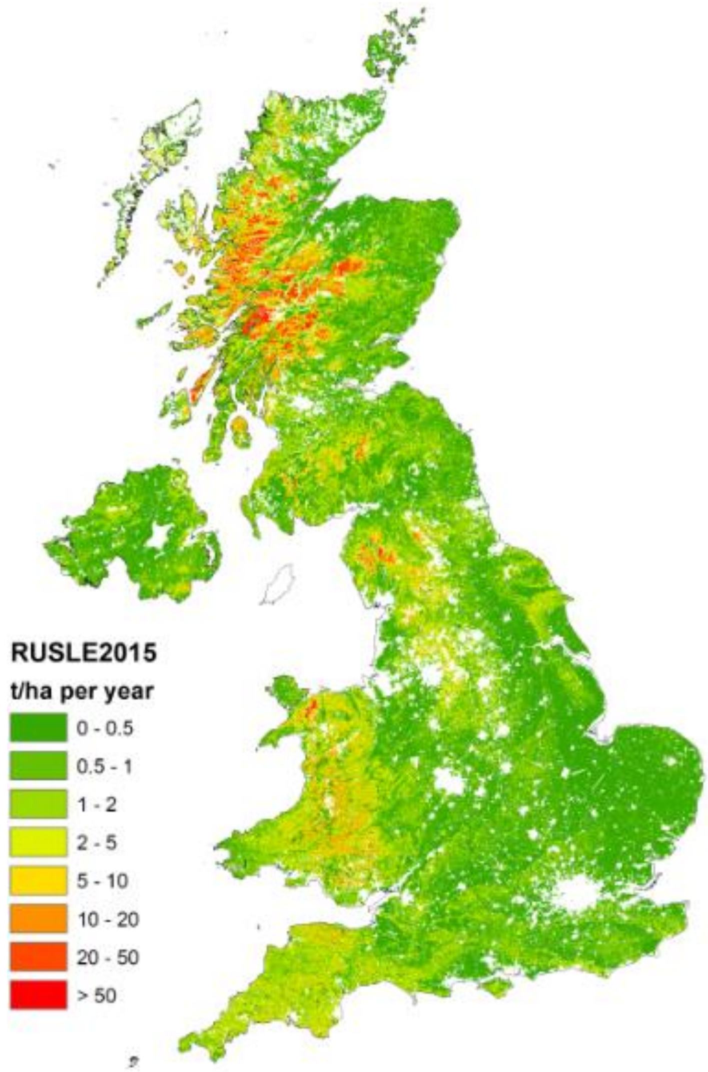


*Figure 14.* ***Map of current soil loss (t/ha/yr) for UK.*** *Data extracted from RUSLE2015 European data (Panagos et al. 2015).*

The number of days per year where heavy rainfall exceeded the daily threshold of 30 mm was calculated for each region and period. Soil losses due to erosion were calculated from RUSLE soil erosion map above (Panagos et al. 2015), scaling per hectare values by the area of arable land in each region. Therefore, losses at baseline incorporate all effects of contributing factors such as soil type, topography and crop type, as well as management factors such as tiling. Contributing factors were assumed to remain constant for the assessment period, with the only variable being rainfall. Future values were scaled by the increase in days with heavy rain, assuming a linear relationship between number of days of heavy rainfall and soil erosion losses. The corresponding losses of soil are scaled from current day losses by the change in heavy rainfall, and the area of arable land cover in each region. Soil losses per ha are applied to the area under arable cultivation, derived from CEH Landcover Map 2015. The assessment assumes land use and land management techniques are kept constant.

The number of days with heavy rainfall per year are shown in Table 25. On average across the UK, the number of heavy rain days increases from 1.1 at baseline to 1.4 under a 2 $^{o}$C scenario and to 2.0 under a 4 $^{o}$C scenario. In England the number of heavy rain days increases from 0.6 at baseline to 0.9 and 1.1 respectively. In Wales with higher rainfall, it increases from 2.9 to 3.5 and 4.8 days. In

Scotland, from a baseline frequency of 1.9 days there is a slight decrease to 1.7 under a 2 °C scenario, due to the projected changes in heavy rainfall in that climate scenario, but a doubling to 3.9 under a 4 °C scenario. In Northern Ireland, it increases from 0.5 at baseline and remains at 1.1 for both the 2 °C and 4 °C scenarios. For any particular region, the projections are highly variable, with values in a 2 °C scenario sometimes lower than baseline or higher than in a 4 °C scenario. In particular, for England the south and east appear to experience fewer intense rainfall days under 4 °C than under 2 °C.

*Table 25.* ***Number of days with heavy rain > 30 mm per year. Average over ten year period for baseline (2001 – 2010), 2 °C and 4 °C scenarios.***

| **Region** | **Baseline (2001-2010)** | **2 °C** | **4 °C** |
|---|---|---|---|
| North West England | 2.2 | 1.8 | 4.2 |
| North East England | 1.2 | 1.6 | 0.9 |
| Yorkshire and Humber | 0.3 | 1 | 0.6 |
| West Midlands | 0.1 | 0.8 | 0.4 |
| East Midlands | 0.1 | 0.9 | 0.4 |
| East of England | 0.1 | 0.6 | 0.3 |
| South West England | 0.4 | 0.8 | 1.3 |
| South East England | 0.4 | 0.4 | 0.5 |
| London | 0.3 | 0.6 | 0.9 |
| Wales | 2.9 | 3.5 | 4.8 |
| North Scotland | 1.8 | 2 | 3.1 |
| West Scotland | 3.3 | 2.8 | 7.6 |
| East Scotland | 0.7 | 0.4 | 1 |
| Northern Ireland | 0.5 | 1.1 | 1.1 |
| | | | |
| England (average of regions) | 0.6 | 0.9 | 1.1 |
| Wales | 2.9 | 3.5 | 4.8 |
| Scotland (average of regions) | 1.9 | 1.7 | 3.9 |
| Northern Ireland | 0.5 | 1.1 | 1.1 |
| **UK (average of regions)** | **1.0** | **1.3** | **1.9** |

Total soil losses (Table 26) at a UK scale increase from 4.2 million tonnes per year by approximately a factor of three under a 2°C scenario, to 14 million tonnes per year, but to a lesser extent under a 4 °C scenario to 11 million tonnes. This is due to the relative change in rainfall intensity in regions with higher or lower arable area. Those with the largest arable area such as East of England and the East Midlands are regions where the increase in rainfall intensity is projected to be lower in the 4 °C scenario later this century than in the 2 °C scenario. Our baseline figure of 3.6 million tonnes per year for England and Wales is slightly higher than other estimates of 2.9 million tonnes per year (Graves et al. 2011; Graves et al. 2015).

*Table 26.* ***Annual tonnes of soil loss by region. Average over ten year period for baseline (2001 – 2010), 2 °C and 4 °C scenarios.***

| | | **Total arable soil loss (t/yr)** | | |
|---|---|---|---|---|
| **Region** | **Arable Area (ha)** | **Baseline (2001-2010)** | **2 °C** | **4 °C** |
| North West England | 153,101 | 107,000 | 88,000 | 205,000 |
| North East England | 186,768 | 173,000 | 231,000 | 130,000 |
| Yorkshire and Humber | 604,082 | 441,000 | 1,471,000 | 883,000 |
| West Midlands | 430,869 | 343,000 | 2,749,000 | 1,375,000 |
| East Midlands | 855,947 | 467,000 | 4,202,000 | 1,868,000 |
| East of England | 1,197,457 | 365,000 | 2,193,000 | 1,097,000 |
| South West England | 649,703 | 1,082,000 | 2,164,000 | 3,516,000 |
| South East England | 610,152 | 494,000 | 494,000 | 617,000 |
| London | 5,667 | 4,000 | 8,000 | 11,000 |
| Wales | 94,794 | 148,000 | 179,000 | 245,000 |
| North Scotland | 62,362 | 36,000 | 40,000 | 62,000 |
| West Scotland | 79,296 | 110,000 | 93,000 | 253,000 |
| East Scotland | 518,989 | 467,000 | 267,000 | 667,000 |
| Northern Ireland | 91,212 | 56,000 | 124,000 | 124,000 |
| | | | | |
| England (total) | 4,693,746 | 3,478,000 | 13,601,000 | 9,702,000 |
| Wales (total) | 94,794 | 148,000 | 179,000 | 245,000 |
| Scotland (total) | 660,647 | 613,000 | 400,000 | 983,000 |
| Northern Ireland (total) | 91,212 | 56,000 | 124,000 | 124,000 |
| **UK (total)** | **5,540,399** | **4,296,000** | **14,304,000** | **11,054,000** |

### 6.6.4 Economic assessment – impact on goods and services

In this assessment, we estimate monetary impacts from lost agricultural crop production as a result of soil erosion. We acknowledge that there are many other impacts of soil erosion which are not valued here. We start by obtaining estimates of soil erosion rates on arable land and calculating the change in soil erosion between the baseline and warming scenarios.

Next, we determined the relationship between soil erosion and crop yields. Soil erosion has been shown to reduce land fertility and lead to lower crop yields globally (Panagos et al, 2017). To calculate the overall reduction in crop yield resulting from soil erosion, we use the findings from Rickson et al (2010) who summarise the results of several studies on impacts of soil erosion on crop yield in the UK and find that yields generally decline by 0.05% for every tonne of soil eroded on UK farmland. We chose to focus on the impacts on crop production rather than other ecosystem services that could be affected by soil erosion, including loss of soil carbon or increased siltation in rivers, since productivity impacts are the most well understood impacts of soil loss in the UK.

We value losses due to the reduction in crop yield by assuming that yield is directly proportional to farm revenues. We expect this assumption to hold true if farm inputs and crop prices remain constant regardless of crop yields. As we are estimating losses arising from changes in crop yields, we only examine farms classified by government surveys as producing cereals, oilseeds and other general crops. We obtain average revenue per farm under the baseline scenario using Farm Business Income data from the 2017 Farm Business Survey, conducted by Defra in England and the relevant government departments in Scotland, Wales and Northern Ireland. We scale farm revenues up to the regional level using data on the number of farms in each region from the June 2017 Survey of Agriculture and Horticulture.

To calculate the revenue loss due to soil erosion in each region under the 2 °C and 4 °C scenarios, we multiply the reduction in crop yield due to soil erosion by farm revenue. These are shown in Table 27.

Annual monetary losses from soil erosion due to heavy rainfall in the whole of the UK are estimated to be £2.6 million per year at baseline. The baseline losses are lower than, but the same magnitude as, those presented by a similar study by Graves et al. (2011; 2015). Those authors estimated total costs of soil degradation in England and Wales at £1.2 billion per year. However, only 20% of the estimated annual costs of soil degradation are associated with loss of provisioning services linked with agricultural productivity. (The remaining 80% of total annual degradation costs are associated with loss of regulating services, including GHG emissions (49%), flood related costs (19%) and water quality related costs (11%)). When broken down to just estimates of annual agricultural yield losses due to erosion, the values of Graves et al. amount to £ 5.3 million per year for all agricultural land cover types, and £3.6 million per year for arable and horticultural soil, so broadly consistent with the estimates in this report.

Losses in crop yield due to soil erosion increase to £8.1 million per year under the 2 °C scenario due to higher incidences of heavy rainfall events. Losses under a 4 °C scenario are lower, however, at £6.5 million per year due to changes in the amount of intense rainfall in that model ensemble. Most of these losses are in England, particularly in the Midlands, with farm revenues expected to decline by £1.8 million in the West Midlands and £1.5 million in the East Midlands compared with baseline under the 2 °C scenario. By contrast, farm losses due to soil erosion are estimated to decrease in North West England and Scotland as soil erosion will be lower in a 2 °C scenario compared to the baseline since climate model ensembles predict fewer heavy rainfall events in these areas.

*Table 27.* ***Annual economic losses in crop production by region. Average over ten year period for 2 °C and 4 °C scenarios****. Baseline losses not calculated in this methodology. n.d. = no data.*

| Region | Number of Farms | Farm Revenue (£m/Year) | Monetary Losses (£m/Year) | | |
|---|---|---|---|---|---|
| | | | **Baseline** | **2 °C** | **4 °C** |
| North West England | 2,436 | 201 | 0.07 | 0.06 | 0.1 |
| North East England | 1,216 | 170 | 0.08 | 0.1 | 0.6 |
| Yorkshire and Humber | 4,330 | 606 | 0.2 | 0.7 | 0.4 |
| West Midlands | 4,199 | 658 | 0.3 | 2 | 1.0 |
| East Midlands | 5,265 | 690 | 0.2 | 1.7 | 0.8 |
| East of England | 7,361 | 1,273 | 0.2 | 1.1 | 0.6 |
| South West England | 6,472 | 821 | 0.7 | 1.3 | 2.2 |
| South East England | 4,799 | 1,934 | 0.8 | 0.8 | 1.0 |
| London[1] | | | | | |
| Wales[2] | 972 | n.d. | n.d. | n.d. | n.d. |
| North Scotland[3] | | | | | |
| West Scotland[3] | | | | | |
| East Scotland[3] | | | | | |
| Northern Ireland | 795 | 35 | 0.01 | 0.02 | 0.02 |
| | | | | | |
| England (total) | 36,078 | 6,355 | 2.5 | 8.0 | 6.2 |
| Wales (total) | 972 | n.d. | n.d. | n.d. | n.d. |
| Scotland (total) | 4,182 | 283 | 0.1 | 0.1 | 0.3 |
| Northern Ireland (total) | 795 | 35 | 0.01 | 0.02 | 0.2 |
| **UK (total)** | | **6,673** | **2.6** | **8.1** | **6.5** |

1 No arable farms recorded in London; 2 No arable farm data for Wales; 3 See Scotland total

### 6.6.5 Adaptation

Soil is a non-renewable resource and the basis for food, feed, fuel and fibre production and for many critical ecosystem services (FAO, 2013). Soil degradation, through erosion, compaction and the decline in organic matter, is caused by unsustainable land uses and management practices, and exacerbated by extreme climate events. The actions set out for soil health in NAP2 (Defra, 2018) are primarily focused on research and monitoring (with soil metrics yet to be derived) and the 25YEP actions on soil health focus on better information and developing a soil health index. Defra (2017), in response to CCRA2 recommendations, noted that soils are currently protected through outcome-based cross-compliance soils rules and the UK Forestry Standard's Forests and Soils Guidelines, while funding is provided to protect soil and water through UK agri-environment schemes. However, these are good practice guides rather than discrete actions.

Possible adaptation measures that are judged likely to reduce climate change to soils (POST, 2015) include:

- Organic matter (OM) addition to agricultural land;
- Cover crops (or green manures);
- Longer crop rotation and intercropping;
- Non-inversion or reduced tillage to improve soil structure;
- Tree planting in strategic areas to increase water infiltration and reduce erosion and run-off;
- Buffer strips; and
- Investment into research in improved soil management methods, in combination with outreach initiatives to land managers, and monitoring.

Adapting soil and agricultural management processes to improve soil characteristics, such as soil organic matter, compaction, management of field boundaries, access points and adjacent water courses, that encourage water retention, help to reduce erosion and help reduce transport of eroded material off-site. As well as reducing erosion, improving soil characteristics is important for conserving soil carbon as part of climate change mitigation, in addition to improving soil biodiversity, which can have subsequent impacts on wider farmland biodiversity.

Adaptation can also include cultivation of crop species that support lower rates of soil erosion (e.g. oilseed rape rather than maize or potatoes) in areas which are classified as at high risk of soil erosion. As noted in CCC (2015), the area under high erosion risk crops, such as potatoes and sugar beet, has reduced; however, maize production may be accelerating soil erosion in south west England.

Early warning signs of soil degradation include fewer earthworms and other soil biota, lower water infiltration capacity of the soil, evidence of channels or gullies in fields, decreased productivity of the land, and shallower levels of topsoil than in previous years. Indicators for assessing progress include monitoring soil organic carbon and soil erosion rates.

ADAS analysis of mitigation measures for water/soil estimate that, assuming 100% uptake of each measure in England, the following reductions in soil loss can be achieved:

- Establishing in-field grass buffer strips 3.6%
- Riparian buffer strips 6.3%
- Cultivating compacted tillage soils 3.6%
- Cultivating land for crops in spring rather than autumn 2.1%
- Establishing cover crops in the autumn 16.6%.

These estimates are based on England level uptake and impact but the impact is likely to vary considerably locally, depending on the soil erosion risk. In Rickson *et al.,* (2010) a range of impacts are reported, reflecting this spatial variation in soils/rainfall and topography. Estimates of reduced soil loss are as follows:

- Winter cover crops 5-10%
- Mulching 40-78%
- In-field buffer strips 5-50%
- Riparian buffer strips 5-84%
- Agro-forestry 65%
- Land use change of arable land to pasture 30-80%.

Measures such as these can be implemented to mitigate the risk of soil loss and could be effective in reducing the impact of crossing the threshold. However, it is likely that more substantive action, e.g. land use change, is necessary to prevent soil loss on high risk sites. Likewise, if the threshold is reached and productive capacity is lost, it may be possible to maintain value in the land through converting this to grassland or woodland. In these instances land use change may be the only viable approach, e.g. to forestry or grassland (from cropping).

In practice, soil loss also pollutes rivers and lakes, affecting ecosystems, with secondary impacts on flooding. These costs are greater than for lost productivity alone. As such, the 'polluter pays' principle applies whereby land managers can be required to change land use or management to avoid erosion. In England, this could include a requirement for land users to prevent bare soil at all times in order to obtain payments within the Environmental Land Managements scheme, which is being developed by Defra. The requirements under Farming Rules for Water in England already apply the polluter pays principle requiring farmers to take action to tackle soil erosion where it impacts on water quality.

NAP actions include:

- Incentivise good soil management practices that enhance soil's ability to deliver environmental benefits through future environmental land management schemes to ensure soils are healthy and productive
- Support research and monitoring to give us a clearer picture of how soil health supports our wider environment goals

While these actions can be delivered through advice, knowledge exchange and incentive based schemes e.g. future environmental land management schemes, they rely on voluntary uptake of measures. This may or may not be sufficient to change behaviours and practices and restore degraded soils to avoid thresholds being crossed e.g. permanent loss of productive capacity.

As outlined in the 2019 Progress Report to Parliament (CCC, 2019), work is underway by Government to develop a robust and flexible soil monitoring methodology which will be able to answer policy questions on soil health. This methodology will be able to support in monitoring of soil health and demonstrating any patterns in soil erosion. Adaptation approaches are summarised in Table 28.

**What is the impact of current levels of adaptation at mitigating these risks?**

It is difficult to quantify the impact of the current levels of adaptation. Many farmers are improving the characteristics of soil to reduce erosion and promote good soil health as part of environmental land management schemes and commercial good practice. There are also increases in the number of hectares planted with catch or cover crops to protect the soil from erosion; however, the impact of this has not been reported. The impact of soil protection measures has been quantified (see sections above), although this does not directly relate to rainfall events.

*Table 28. Adaptation approaches for rainfall impacts on soil erosion*

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Improve soil characteristics to reduce erosion and help reduce transport of eroded material off-site. | Relies on commercial good practice or voluntary uptake of environmental land management schemes. In England, 0.55% of agricultural land in Countryside Stewardship is under management contracts to improve soil management (includes woodland options) (Natural England 2019).<br><br>In England, some actions are already mandatory under the polluter pays principle e.g. under Farming Rules for Water. | Need to consider data on alignment of AES uptake or land use change with high risk area for soil erosion. | **Delivering adaptation:**<br>Actions: record changes in soil levels at some reference sites in commercial production to act as an early warning system; implement farming practices which reduce soil erosion; prevent bare soil cover wherever possible; potential to change planting dates to avoid periods of high rainfall coinciding with bare soil.<br>Capacity is largely available for these actions at present, however, uptake is voluntary. Therefore adaptation may require regulation or improved incentives in order to stimulate the required level of action to prevent the threshold effect.<br>Regulation: Impacts of soil erosion are mainly a public cost (e.g. flooding, water treatment)<br>Advice: Where farmers recognise the private benefits of avoiding soil loss, information and advice can change behaviours and drive effective autonomous adaptation.<br>The new environmental land management schemes in the UK post-Brexit provide a basis for incentivising | **Delivering adaptation:**<br>Delivering adaptation within the next 5 years will have the potential to slow down the rate of soil loss. Early action would increase resilience of soil against erosion, reduce the cost of many impacts associated with soil loss (water quality, flooding, lost natural capital) and reduce the risk of lock-in. Adaptation can be delivered promptly as cropping systems readily change.<br>The new environmental land management schemes in the UK post-Brexit will apply from 2023 but adaptation options need to be built into design and piloting [2019-2023]. Changes to regulation and advice provision are also being developed as part of the 25YEP. As such, action in the next 5 years to build CC adaptation to agriculture policy is a priority.<br>Each year where no action is taken will likely increase the cost of adaptation, as well as shorten the timeframe in which adaptation |
| Support research and monitoring of soil health | The 25YEP (HM Government 2018) states that Defra will invest to help develop ‘meaningful metrics that will allow us to assess soil | N/A | | |

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<td>improvements and to develop cost-effective and innovative ways to monitor soil at the farm and national level’. Defra is investing at least £200,000 to help develop soil health metrics and test them on farms across the country. Two pieces of research have been funded to date (CCC, 2019).</td>
<td></td>
<td rowspan="4">relevant change in land management – this is especially important for soil erosion as action may be needed elsewhere in the river system e.g. reducing run-off, slowing river flow or providing water storage, and because in the short term the costs of preventing soil erosion are greater than the benefits accrued from preventing it. Capital grants can incentivise infrastructure to manage erosion.<br>Beyond the threshold, land use change to woodland or grassland may be required if agricultural land has lost productivity.<br><br>Building capacity:<br>There is huge scope for improving awareness of future climate impacts and adaptation responses available in the agriculture sector. This needs to be targeted spatially and focused on the economic case as well as the public good aspect.<br>Research and monitoring of how soil health supports wider environment goals to promote understanding and need for action by users will be useful for building capacity.<br>Technologies for reducing soil erosion are widely available, and therefore the capacity is largely available, but action</td>
<td rowspan="4">needs to be carried out in order to prevent the threshold effect.<br><br>Building capacity:<br>Benefits are available within a 5-year period in terms of many soil erosion adaptations as annual cropping systems readily change, therefore there is a strong case for action in the near term. Small changes in land management can have a big impact on retaining soil health, which will make soils less susceptible to erosion. Action taken now to improve understanding and accessibility of technologies which prevent soil erosion is important as there is lock-in risk of losing agricultural productivity and reducing the area of agricultural land.</td>
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<tr>
<td>In-field management.<br><u>Cropping</u> – tramline management, cover crops (winter cover), buffer strips, high-density planting and sediment traps.<br><u>Grassland</u> – reduced stocking density, use of swales</td>
<td rowspan="3">Relies on commercial good practice or voluntary uptake of environmental land management schemes (but note mandatory Farming Rules for Water to protect water quality in England). In England, 0.55% of agricultural land in Countryside Stewardship is under management contracts to improve soil management (includes woodland options). Ecological Focus Area (EFA) measures include</td>
<td>In 2015/2016, 55,900 ha were planted with cover or catch crops as an EFA feature, representing a 45% increase from the previous season (Defra, 2017)</td>
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<td>Reduced cultivation approach - no till/min-till (cropping)</td>
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<td>Land use change – from arable to grassland, agro-forestry or forestry.</td>
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| | | | | |
|---|---|---|---|---|
| | buffer strips and cover crops which help to protect water courses from DWPA (Posthumus *et al.,* 2013). To achieve net-zero, woodland cover in the UK need to increase from 13% to around 17-19% by 2050 (CCC, 2020). | | depends on the incentives provided to take action and understanding how to implement these methods to maintain farm profitability. | |

**Is risk managed by reactive or planned adaptation?**

The risk is managed by reactive adaptation where the erosion is significant and makes existing commercial production/system uneconomic but there is a case to incentivise a change in land use or management where this is perceived to be uneconomic. Many erosion control measures result in short-term negative economic returns, even if benefits will accrue is future years through soil retention and land productivity as well as land value; as such, farmers are generally reluctant to implement erosion control measures without compensation (Posthumus *et al.,* 2013). Education of the farmer about loss of their own natural capital can be important to promote action here. There is therefore a need for targeted incentives to promote specific actions e.g. for buffer strips, arable reversion, afforestation or investment in no/low till equipment. Nevertheless, there should be recourse to regulation where societal impacts are high, this could include fines for sediment pollution.

**Risks of lock-in**

Permanent loss of soil and productive capacity of land.
Land use change to alternative activities could risk lock in.

**Risk(s) interacting**

Soil loss also pollutes rivers and lakes, transporting both nutrients sediment and agrochemicals into freshwater systems.
Soil erosion is a contributor to urban and other flooding.
Increased fertiliser use to compensate for lost soil fertility is a major interacting risk with wider implications for water quality and greenhouse gas emissions.

**Urgency scoring**

More urgent: More action needed - Early action would have benefits and build resilience as well as reduce the risk of lock-in. This would be a no and low regret adaptation. Beyond this, land use change to woodland or grassland may be required if agricultural land has lost productivity but would risk lock in.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Actions such as improving soil characteristics, changes to in-field management (e.g. tramline management, using cover crops, buffer strips, high-density planting, sediment traps), and changes to cultivation (e.g. min-till/no-till) could all be undertaken in advance to reduce the risk of the threshold occurring. Where agricultural land has lost its productivity, land use change to other uses, such as woodland or grassland may be required.

**In what scenarios are there limits to adaptation?**

There may be economic barriers to uptake – many erosion control measures result in negative financial and economic returns and farmers are generally reluctant to implement erosion control measures without compensation (Posthumus *et al.,* 2013).

Where soil is substantially degraded, adaptation measures to protect soil will have little impact. In these cases it is likely that more substantive action, e.g. land use change, is necessary to prevent soil loss on high risk sites; although this would take land out of agricultural production.

# 7 Mountains moors and heaths: peatlands

## 7.1 Summary – Mountains moors and heaths: peatlands

Peatlands are considered a cross-cutting habitat category that encompasses blanket bog and ombrotrophic bogs, as well as lowland fens. The literature review identified four potential thresholds across all peatland types (section 16.3.1). Of those, one impact was taken forward for the national screening assessment: the effect of summer heat on the stability of blanket bogs. The threshold is a long-term temperature average of the warmest month, which is considered to represent a proxy for the combined effects of high summer temperatures and associated low rainfall on peat moisture content. The case study focused on the temperature effects on peatlands in more detail.

*Temperature effects on peatlands carbon balance (Ne 1, Ne 5, Ne 6)*

A long-term average temperature of the warmest month of 14.5 °C defines the climate envelope for peatlands, based on current extent. Exceeding this threshold can lead to drying and desiccation of the peat leading to increased decomposition, damage to *Sphagnum* cover, damage to the soil structure and exposure of bare peat and erosion. In turn this results in a consequent increase in greenhouse gas emissions. Near-natural and rewetted peat are more resilient to these climatic impacts than modified (grass and heather dominated) peatlands. With exceedance of the temperature threshold, peatland changes to increasingly degraded condition categories, but the underlying peat is assumed to remain, albeit with higher greenhouse gas emissions.

At a UK scale, currently there is 2,035,000 ha of peatland (excluding peatland under other land uses), and of this 454,000 ha is in the poorest condition category: highly modified peatland. Under a 2 °C scenario, an additional 53,000 ha shifts to the poorest condition category. This increases to an additional 247,000 ha under a 4 °C scenario (around 12% of UK peatland area). These changes lead to an additional 104,000 $tCO_2e$ and 500,000 $tCO_2e$ (tonnes of greenhouse gas emissions as $CO_2$ equivalent) under a 2 °C and 4 °C scenario respectively.

The annual cost of peatland $CO_2e$ emissions due to climate change increases from £239 million at current day to £318 million under a 2 °C scenario and £1.3 billion under a 4 °C scenario.

Current adaptation focuses on rewetting, which increases resilience of peatlands to fire and other pressures. Further adaptation should involve other management interventions (e.g. changes in grazing or burn management) that favour the survival or re-establishment of key peat-forming species, a functional acrotelm (the spongy upper layer of a peat-forming peatland, which can be lost from degrading systems), and a resilient hummock-hollow topography. For peatlands the area of restored peatland is less than the area moving to unfavourable condition annually, and this is of concern.

**Urgency scoring -** More urgent – more action needed. Action is needed to prevent irreversible damage. This would be a no and low regret adaptation. Restoring peatlands and transformational change in land use in the uplands is both a mitigation and adaptation response.

## 7.2 Overview: Mountains moors and heaths: peatlands – national screening assessment

Peatlands are considered a cross-cutting habitat category that encompasses blanket bog and ombrotrophic bogs, included within the NEA broad habitat of mountain moors and heaths, as well as lowland fens which in the NEA were included in Wetlands. The literature review included all peatlands and identified four potential thresholds across all peatland types, including lowland. Of those, one impact was prioritised for national screening (Table 29), and is discussed in detail in the next sections. The full list of potential impacts identified in the literature review can be found in Section 16.3.

The screening assessment focuses on blanket bogs and is conducted for impacts of temperature on greenhouse gas emissions, using a temperature threshold as the main climatic driver of change for which there is evidence in the literature. A more detailed assessment is covered in a case study, which brings in a wider set of climate data, and applies improved estimates of the circumstances under which change may occur from one peatland condition class to another.

Table 30 shows the extent of UK peatlands (blanket bog and deep peats in both uplands and lowlands) within aggregated condition categories (based on 2013 data reported in Evans et al. 2017, updated with data from UKCEH Edinburgh emissions inventory team). Scotland holds around 72% of the UK peatland resource, and England around 16%, Northern Ireland 8% and Wales 3%.

*Table 29.* ***Potential threshold-driven impacts in mountains moors and heaths, peatlands****.*

| Climate-mediated stressor | Habitat | Threshold | Biophysical response | Societal end-point affected | Aligned risk descriptors |
|---|---|---|---|---|---|
| Temperature | Peatland | 14.5 °C (long-term average temperature of warmest month) | Increase in graminoid abundance and peatland degradation | Carbon sequestration | Ne 1, Ne 5, Ne 6 |

*Table 30.* ***Estimated area (ha) and condition category of UK blanket bogs and deep peat, by country*** *(Based on 2013 data reported in Evans et al. 2017, updated with data from UKCEH Edinburgh emissions inventory team)#. Isle of Man not covered in this report, but figures retained to allow comparison with other data sources.*

| **Region** | **Near natural bog** | **Rewetted bog** | **Modified (grass/heather dominated)** | **Highly modified (eroded and domestic peat-cut)** | **Total (excluding afforested bog, grassland and arable on peat)** |
|---|---|---|---|---|---|
| England | 83,930 | 24,451 | 163,788 | 53,468 | **325,637** |
| Wales | 23,533 | 4,013 | 35,255 | 206 | **63,007** |
| Scotland | 490,497 | 20,416 | 657,889 | 307,164 | **1,475,966** |
| Northern Ireland | 35,110 | 5,347 | 36,618 | 93,142 | **170,218** |
| Isle of Man | 0 | 0 | 13 | 1 | **14** |
| **Total** | **633,070** | **54,226** | **893,564** | **453,981** | **2,034,841** |

# Note this excludes afforested peatlands, and peat under intensive and extensive grassland and under arable. For further description of each peat category see Evans et al. (2017). Re-wetted is treated as a separate category to differentiate restored from near-natural, and because restoration to full ecological function can take decades. Grass dominated heathlands still retain some heathland species, compared with grassland sown or established on degraded peatland. Domestic peat cut excludes commercial horticultural peat extraction.

## 7.3 Temperature effects on greenhouse gas emissions in peatlands

The threshold and assessment chain are summarised in Figure 15. Above an average monthly temperature of 14.5 °C, peatlands are considered to lie outside of their climate envelope in the UK. This results in damage to sphagnum cover and the ecological condition of peatlands, in turn this leads to desiccation, gullying and erosion of the peat surface. This results in greater carbon emissions.

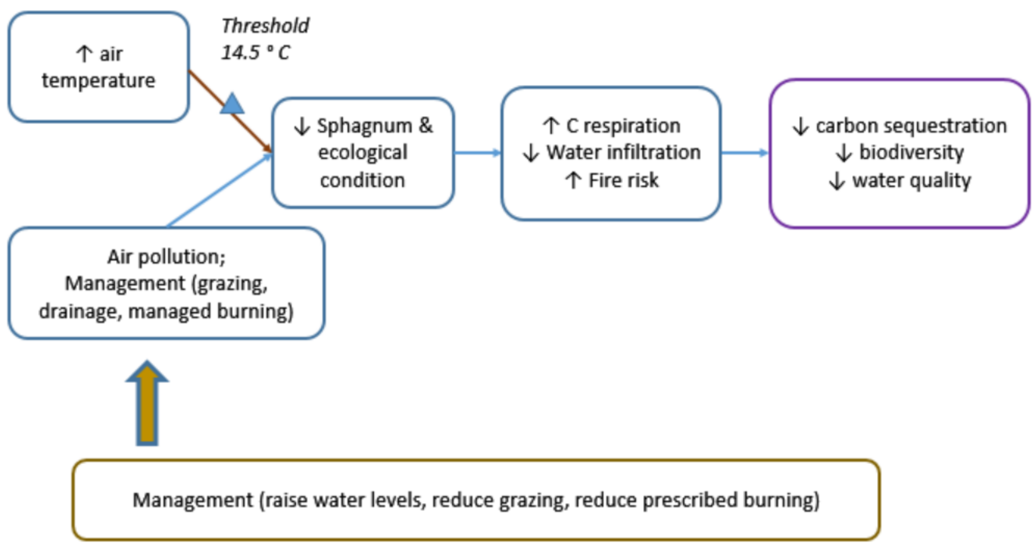


*Figure 15.* ***Impact chain for temperature effects on integrity of peatlands (blanket bog and deep peat).*** *Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures. The screening assessment focuses only on carbon sequestration (GHG emissions).*

### 7.3.1 Justification of threshold used in the assessment

A long-term average temperature of the warmest month of 14.5 °C defines the climate envelope for UK peatlands, based on current extent (e.g. Gallego-Sala et al., 2010). This is considered to represent a proxy for the combined effects of high summer temperatures and associated low rainfall on peat moisture content. Elevated temperatures and $CO_2$ have the potential to increase vegetation productivity, but will also increase carbon loss through respiration, potentially to a greater extent (Brown, et al., 2016). Rising temperatures may also alter plant community structure and function. In an experimental study, Dieleman et al. (2015) described three signs of regime shift in peatland habitats under climate change, based on temperature manipulation experiments. They observed significant reductions in carbon sequestration when peat was warmed by 8 $^oC$ above ambient levels for the study site, due to non-linear decline of *Sphagnum* mosses. Increased graminoid abundance was observed in their 4 $^oC$ warming treatment, sufficient to indirectly affect *Sphagnum* growth through competitive processes. Note that the high temperature thresholds from this study derive from the experimental treatments used, and reflect short-term ecological responses. They may therefore reflect potential effects seen in natural systems over longer periods in response to smaller temperature increases.

A process-based modelling study taking a climate bio-envelope approach suggested that adverse impacts on peat formation were likely to occur above a 30-year mean temperature of 14.5 $^oC$ for the warmest month (Gallego-Sala & Prentice, 2013), and this is the threshold used in this assessment. The impact chain for the resulting ecosystem impacts shown above (Figure 15) is adapted and partly extended from impact chains presented by Evans et al. (2014). Below we discuss in more detail aspects of the threshold and ecological impacts.

#### Inter-relationships between temperature and rainfall

The literature on climate change impacts on peatlands focuses primarily on periods of extreme heat and drought. These generally coincide, and are more likely to result in threshold-type ecosystem changes where the intrinsic resilience of the peatland system has been degraded through other forms of human pressure, notably land-use and atmospheric pollution. To a large extent, these threshold responses are likely to be mediated through changes in the dominance of different plant functional types, which play a fundamental role in the functioning of bog ecosystems, notably their capacity to form new peat. In particular, any pressure resulting in a loss of *Sphagnum* cover and an increase in higher plant cover is likely to reduce peat formation and $CO_2$ uptake, and may cause the peatland to become a net $CO_2$ source (e.g. Bragazza et al., 2016). Under more severe levels of climate- or management-related disturbance, partial or complete loss of peat vegetation cover can lead to severe carbon loss through a combination of peat oxidation, water and wind erosion.

Temperature and drought effects often co-occur, since droughts tend to occur during long hot spells in summer, although they can be compounded by low winter rainfall. Both temperature and drought may significantly perturb peatland ecosystems in the UK. While they have different mechanisms of impact, the net effect on peatlands is similar, i.e. a shift to degraded peatland which is no longer peat forming, typically characterised by a loss of sphagnum, an increase in grasses and *Calluna*, which may also be associated with increased area of bare peat.

During drought periods the abundance of graminoids and saprotrophic fungi in peatlands may increase. This shift in plant and soil communities leads to greater levels of respiration compared with sphagnum dominated peatland. These effects of drought become prevalent when water table levels drop below 24cm (Jassey, et al., 2017). Drought is increasingly considered to be the most influential factor on function, formation, and net $CO_2$ exchange in peatlands. However, intact peatlands are relatively resilient to occasional drought. If water tables are lowered significantly, and/or the frequency and severity of droughts increases, then peatland habitats have the potential to become $CO_2$ sources (Lund, Christensen, Lindroth, & Schubert, 2012). This has implications for biodiversity in upland areas, particularly birds (Pearce-Higgins & Yalden 2004; Pearce-Higgins 2011). A modelling study showed that a fall in water tables will impact crane-fly (tipulid) abundance and populations of bird predators that feed on them including dunlin, red grouse, golden plover (Carroll et al. 2015). While a threshold has been identified linked to drought, the link between water tables in peatlands and rainfall inputs is highly complex and cannot be simplified sufficiently for the purposes of a national level screening assessment.

The assessment focuses on a temperature threshold – specifically the temperature of the warmest month – on the basis that this has been shown to be a good predictor of blanket bog presence/absence in a number of climate envelope modelling studies, both in the UK (Gallego-Sala et al., 2010; Clark et al., 2010; Ferreto et al., 2019) and globally (Gallego-Sala and Prentice, 2013). In reality, climate impacts will also be associated with changes in rainfall, particularly summer drought, and mediated through changes in internal ecosystem properties such as water table depth that are also affected by factors such as landscape position and management (e.g. Carroll et al., 2015). However, our understanding of the precise climatic conditions that limit peat bog formation are still not fully resolved. For example, studies of UK blanket bog suggest a minimum value for blanket bog occurrence of 1000 to 1200 mm $yr^{-1}$; Clark et al., 2010). However, blanket bogs are known to form in other cool temperate areas where annual rainfall is well below the minimum thresholds cited in the papers above (e.g. annual rainfall in the Falkland Islands, which have the highest proportional blanket bog cover in the world, is generally below 600 mm $yr^{-1}$. Similarly, blanket bogs are known to occur in other warmer regions such as Spain, outside the apparent climate space of UK blanket bogs.

This suggests that the resilience of peatlands to specific combinations of temperature and rainfall depends on a complex set of physical properties and hydrological factors that are beyond the scope of this assessment exercise. On the basis that the most direct impact of rainfall is likely to be through summer drought, and that this is to a large extent correlated with high summer temperatures, we have taken the long-term monthly temperature of the warmest month to be the most tractable proxy for quantifying ecosystem impacts on peatlands at national scale.

### Threshold-related ecological responses

The impact chain highlights the extent to which multiple anthropogenic pressures (including climate change) interact to alter the state of the ecosystem, and subsequently its function and capacity to support or regulate societally important ecosystem services. To some extent these causal relationships represent long-term responses to long-term pressures. These may operate linearly (i.e. an incremental increase in one pressure will produce an equivalent incremental change in ecosystem functions and services), non-linearly (i.e. ecosystem may respond to a greater or lesser extent depending on the range over which a pressure changes), or interactively (i.e. the ecosystem may respond unpredictably and potentially in a threshold-type way to a combination of different pressures) (Evans et al., 2014). However, acute climate-related effects such as droughts or fires which introduce short-term perturbations are often the trigger which initiates ecological change such as a shift in vegetation communities or a physical change in the peat structure. For example, Sherwood et al. (2013) showed that a combination of drainage then wildfire led to the exposure of denser subsurface peat, reducing near-surface water holding capacity and inhibiting *Sphagnum* recovery. Chronic long-term changes can thus act to reduce the resilience of the system to recover from acute effects.

Non-linear and interactive relationships raise the possibility of threshold-type responses, and indeed there is evidence for these types of change in historical and palaeo records. Examples include the widespread loss of *Sphagnum* that resulted from atmospheric sulphur pollution during the 20th century (Tallis, 1987), and the replacement of natural blanket bog communities by purple moor grass (*Molinia caerulea*) which took place across large areas of South Wales, Northern and Southwest England from the 19th century onwards, which is believed to result from a combination of overgrazing, burning and atmospheric nitrogen pollution (Chambers et al., 2007; Hughes et al., 2007). The role of extreme climate events as triggers of long-term change is uncertain. However there is strong evidence that periods of summer heat and drought can affect peat condition in the short and medium terms. This is primarily associated with water table drawdown, which exposes normally waterlogged peat to aerobic decomposition. Freeman et al. (2001) proposed that drought events could effectively release environmental constraints on enzymic processes (the so-called 'enzymic latch') which could in theory lead to sustained increases in decomposition. This concept has been invoked as a potential trigger for long-term peat destabilisation (e.g. Worrall and Burt, 2004; Fenner and Freeman, 2011; Brouns et al., 2014). However, it is important to note that periodic droughts are a natural occurrence, and the persistence of many of the UK's peatlands over millennia strongly suggests that they are resilient to short-term perturbation under natural conditions. Furthermore, other studies have suggested that increases in $CO_2$ emission are limited to the period of water table drawdown, with relatively rapid ecological recovery (e.g. Estop-Aragones and Blodau, 2012).

The evidence discussed above suggests clear potential for non-linear impacts of change in peatlands. Evidence for irreversible 'tipping point' type threshold responses of peatlands to climate events is more limited, but still suggests the potential for irreversible effects. Bragazza (2008) reported ecosystem scale, sustained (> 4 years) degradation of bogs in the Italian Alps following an extreme hot and dry period in 2003. This was associated with the desiccation and mortality of *Sphagnum*. Potentially irreversible degradation of peatlands can also occur if peat dries out to the extent that it becomes hydrophobic (which can happen for example in eroding areas where bare peat is exposed) as the structurally altered peat will not re-wet. In the longer term, loss of the surficial peat layer (acrotelm - the spongy upper layer of a peat-forming peatland) can leave the denser, nutrient-depleted and less water-permeable 'catotelm' layer exposed, and also lead to the loss of microtopography (hummock-hollow structures) that confer resilience and adaptation capacity to the ecosystem, creating conditions unfavourable to *Sphagnum* recovery (Lindsay, 2010; Sherwood et al., 2013). These single-layered, topographically simplified 'haplotelmic' bogs are characteristic of areas that have been degraded by land-use pressures, and may be particularly susceptible to climate change (Lindsay, 2010). The formation of subsurface pipes in degraded (especially drained) bogs may also lead to a loss of climate change resilience due to the long-term loss of water retention capacity and increased runoff and erosion rates (Holden et al. 2012a).

### The role of contributing factors

However, it is less clear whether peatlands can withstand periodic droughts if they are also subjected to other pressures such as land-use (e.g. drainage, burning or heavy grazing) and atmospheric pollution, or whether even an undisturbed peatland will be able to withstand more severe or frequent droughts resulting from climate change. Using a bioclimatic envelope modelling approach, Clark et al. (2010) and Gallego-Sala et al. (2010) suggested that blanket bogs might no longer be able to form in more climatically marginal (warmer, dryer) regions of Eastern Scotland, Northeast England and Southwest England. Similar findings have been obtained for Ireland (Coll et al., 2014), Scotland (Ferreto et al., 2019) and for the global blanket bog area (Gallego-Sala and Prentice, 2013). However the bioclimatic envelope approach has been criticised as it does not take account of the intrinsic resilience of existing peatlands or the role of management in altering this resilience, and is frequently dependent on the dataset used to parameterise the model (for example, blanket bogs occur in Northern Spain, outside the apparent climate space of UK blanket bogs).

Issues related to burning and wildfire operate to some extent separately from the remainder of the causal chain, and also because the causal relationships are somewhat disputed. Wildfires on peatland are generally started by people rather than natural events e.g. lightning, and are therefore linked to societal issues such as public access and exclusion. Where wildfires do occur, these have severe impacts on the other societal outcomes as they lead to large $CO_2$ emissions (and other forms of air pollution with potential to affect human health), elevated flood and erosion risk, and decreased water quality. With regard to the role of managed burning, its impacts on the carbon balance, water quality and biodiversity have been heavily debated (e.g. Yallop & Clutterbuck 2009; Holden et al. 2012b; Brown et al., 2014; Davies et al. 2016; Ashby & Heinemeyer 2019; Marrs et al., 2019; Baird et al., 2019) and remain somewhat uncertain. It has recently been argued that the managed burning of blanket bogs for grouse production represents an effective form of mitigation against climate change related wildfire risk (Marrs et al., 2018). According to this view, the moderate loss of $CO_2$ sequestration resulting from repeated prescribed burns (Marrs et al., 2018; Garnett et al. 2010) could be considered less damaging in the long term than a zero-burn approach that allows woody *Callluna* biomass to accumulate and thereby increases the risk of wildfires, which could have more severe consequences in terms of peat carbon loss. However this argument presupposes that *Calluna*-dominance is the natural endpoint of blanket bogs, which is not the case – the dominance of *Calluna* in areas such as the Pennines (where the Marrs et al. study took place) is a reflection of the land-use and atmospheric pollution history of the area, which have resulted in an ecosystem that is unnaturally dry and denuded of its natural *Sphagnum* cover. A wet (or re-wetted) peatland generally has an extensive and accumulating Sphagnum cover which restricts the amount of *Calluna* or other woody biomass that can accumulate, while the high water table restricts the extent to which any fires that do occur can burn into the underlying peat. The Marrs et al. (2018) study has been challenged in a rebuttal by Baird et al. (2019). On the basis of these arguments we would not recommend that managed burning be considered an effective form of climate change mitigation.

Overall, the available evidence suggests that peatlands in their natural condition (i.e. wet, with a functional acrotelm and hummock-hollow topography) are likely to be fairly resilient to climate change, as they have intrinsic capacity to withstand short-term climatic perturbations, as indeed they have throughout the Holocene[16]. Peatlands that have been degraded through drainage, burn-management, overgrazing and air pollution often lack these resilience characteristics and are vulnerable to climatic impacts including species change, carbon loss and erosion. Peatlands that are currently in a marginal state (for example those with lowered water tables that retain some

[16] The last ~11,000 years

*Sphagnum* cover) may be particularly vulnerable to threshold-type changes in response to additional climatic pressures, and are therefore a high priority for adaptation.

### 7.3.2 Impacts on natural assets and the services they provide

Exceeding the 14.5 °C temperature threshold can lead to drying and desiccation of the peat leading to increased decomposition, damage to vegetation such as *Sphagnum* cover, damage to the soil structure and exposure of bare peat and erosion. In turn this results in a consequent increase in greenhouse gas emissions. Near-natural and rewetted peat are more resilient to these climatic impacts than modified (grass and heather dominated) peatlands, due to their greater capacity to retain water and to adjust to changing conditions, for example through surface movement ('bog breathing'). With exceedance of the temperature threshold, peatland changes to increasingly degraded condition categories, but the underlying peat is assumed to persist, albeit with higher greenhouse gas emissions.

Peatland degradation will compromise the majority of ecosystem services that they provide, with the greatest impacts on their role as an active carbon sink and store of accumulated carbon, the biodiversity they support, and their capacity to regulate the quantity and quality of water. This includes drinking water supplies in regions such as the Pennines where they form an important part of the water supply.

### 7.3.3 Ecosystem assessment – climate hazard thresholds

In this assessment we use the threshold of monthly mean temperature of 14.5 $^{o}$C for the warmest month, and assess the frequency that the threshold is exceeded over a decade. The assessment focuses on carbon emissions resulting from exceedance of this temperature threshold. The broader suite of ecosystem services delivered by peatlands (e.g. water filtration, biodiversity) are not considered within the scope of this study.

Table 31 shows the number of years per decade when mean temperature of the warmest month exceeded 14.5 $^{o}$C. Under a 4 $^{o}$C scenario, most areas of the UK will exceed the threshold for the majority of years. For the UK as a whole, the threshold will be exceeded on average 5.6 years in ten under a 2 $^{o}$C scenario and 8.9 years in ten under a 4 $^{o}$C scenario. In England and Wales the threshold will be exceeded around six years out of ten under a 2 $^{o}$C scenario, and nine years out of ten under a 4 $^{o}$C scenario. Northern Ireland and Scotland show negligible exceedance under a 2 $^{o}$C scenario, but reach comparable levels of exceedance (seven to eight years out of ten) under a 4 $^{o}$C scenario.

When the temperature threshold is exceeded, a proportion of the existing habitat is likely to change to a degraded state. Peatlands that are already degraded by land-use pressures are likely to be particularly vulnerable to additional climate pressures, as discussed above. Where the temperature threshold is exceeded for multiple years in a decade, the impacts will be greater.

*Table 31.* ***Number of years per decade where the mean air temperature of the warmest month exceeds 14.5 °C*** *(after adjusting for typical elevation of blanket bog in each region).*

| **Region** | **2 °C** | **4 °C** |
|---|---|---|
| England | 5.5 | 9 |
| Wales | 6 | 9 |
| Scotland | 0.7 | 7 |
| NI | 0 | 8 |
| **UK (average of regions)** | **5.6** | **8.9** |

For the rapid screening assessment, conversion factors were estimated for the likely change to degraded habitat (Table 32), in discussion with peatland experts. These assume that for low exceedance (1-4 years per decade) near-natural bog and rewetted bog retain high water tables and are sufficiently resilient to avoid degradation. However, the modified grass- and heather-dominated communities will have an increased risk of further degradation to a state where part of the modified peatlands become actively eroding. It was estimated that 10% of the habitat in this condition at baseline will shift to the highly modified category. Under high levels of threshold exceedance, taken as > 4 years per decade (Bragazza, 2008), the assumption is that near-natural and rewetted bogs are not sufficiently resilient to avoid change and 10% of the habitat at baseline will shift to the highly modified category. The degradation rate will increase in the modified grass and heather dominated category, with 20% converted to the highly modified category.

*Table 32.* ***Conversion factors to calculate change in habitat when the mean temperature of warmest month is exceeded****.*

| | | Proportion of habitat which shifts to a Highly modified peatland category | | |
|---|---|---|---|---|
| | No. yrs per decade exceeding threshold | Near natural bog | Modified (Grass/Heather dominated) | Rewetted bog |
| Low exceedance | 1-4 | 0 | 0.1 | 0 |
| High exceedance | >4 | 0.1 | 0.2 | 0.1 |

The following two tables show: the area of each habitat that shifts to the highly modified peatland category as a result of threshold exceedance (Table 33), and the resulting total habitat area in each condition category for each scenario (Table 34).

Across the UK as a whole (Table 33), under a 2 °C scenario, 53,000 ha becomes eroded (~ 2.6% of the total UK blanket bog resource), while under a 4 °C scenario this figure is five times higher at 247,000 ha (~ 12% of the UK blanket bog resource). In England the area that becomes eroded increases by 43,000 ha under a 2 °C scenario but remains the same in this assessment under a 4 °C scenario, since the exceedance already falls into the high impact category.  The eroded area within this category is likely to increase further with greater exceedance of the temperature threshold. In Wales, a similar pattern emerges, with eroded area increasing by 9,000 ha in both scenarios. In Scotland where there is no exceedance of the threshold under a 2 $^{o}$C scenario, the eroded area dramatically increases to 182,000 ha under a 4 $^{o}$C scenario. A similar pattern occurs in Northern Ireland when threshold exceedance under a 4 $^{o}$C scenario leads to the eroded area increasing by 11,000 ha.

In terms of total habitat area (Table 34), in Scotland which holds the largest peatland resource, the area which is highly modified increases from 307,000 ha at baseline and under 2 $^{o}$C to 489,000 under 4 $^{o}$C scenario. In England the area highly modified almost doubles to 97,000 under a 4 $^{o}$C scenario, while in Wales the area increases substantially from 200 ha at baseline to 10,000 ha under a 4 $^{o}$C scenario. The increase in Northern Ireland is less substantial, rising from 93,000 ha to 104,000 ha under a 4 $^{o}$C scenario.

Given that these predictions are based on a simple threshold response to a single climate variable, and are based on spatially aggregated data, they should be treated as indicative of potential risks, rather than as quantitatively accurate predictions of change. Nevertheless, they do suggest that currently predicted changes in climate, particularly under the 4 °C scenario, could have societally relevant impacts on blanket bog function. A shift towards more heavily modified peat condition categories will be associated with an increase in $CO_2$ emissions, further contributing to climate change. Where gully erosion becomes established within previously intact blanket bogs, this may become self-perpetuating and effectively irreversible without major restoration interventions, leading to high and sustained rates of carbon loss. Peat erosion will also lead to higher sediment loadings to rivers and water supplies, with detrimental impacts on water quality and drinking water supplies.

*Table 33.* ***Net change in habitat (ha) to highly modified peatland.*** *Figures rounded to nearest '000.*

| | 2 °C | | | | 4 °C | | | |
|---|---|---|---|---|---|---|---|---|
| | Near natural | Modified | Rewetted bog | All categories | Near natural | Modified | Rewetted bog | All categories |
| England | -8,000 | -33,000 | -2,000 | -44,000 | -8,000 | -33,000 | -2,000 | -44,000 |
| Wales | -2,000 | -7,000 | -400 | -10,000 | -2,000 | -7,000 | -400 | -10,000 |
| Scotland | 0 | 0 | 0 | 0 | -49,000 | -132,000 | -2,000 | -183,000 |
| NI | 0 | 0 | 0 | 0 | -4,000 | -7,000 | -500 | -11,000 |
| **UK (total)** | **-11,000** | **-40,000** | **-3,000** | **-53,000** | **-63,000** | **-179,000** | **-5,000** | **-247,000** |

*Table 34.* ***Area of peatland (ha) in aggregate condition categories. Baseline data adapted from Evans et al. 2017 (see Table 30), future projected impacts due to climate under 2 °C and 4 °C scenarios.*** *Figures rounded to nearest '000.*

| | Baseline | | | | 2 °C | | | | 4 °C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Near natural | Modified | Rewetted bog | **Highly modified** | Near natural | Modified | Rewetted bog | **Highly modified** | Near natural | Modified | Rewetted bog | **Highly modified** |
| England | 84,000 | 164,000 | 24,000 | 53,000 | 76,000 | 131,000 | 22,000 | 97,000 | 76,000 | 131,000 | 22,000 | 97,000 |
| Wales | 24,000 | 35,000 | 4,000 | 0 | 21,000 | 28,000 | 4,000 | 10,000 | 21,000 | 28,000 | 4,000 | 10,000 |
| Scotland | 490,000 | 658,000 | 20,000 | 307,000 | 490,000 | 658,000 | 20,000 | 307,000 | 441,000 | 526,000 | 18,000 | 490,000 |
| NI | 35,000 | 37,000 | 5,000 | 93,000 | 35,000 | 37,000 | 5,000 | 93,000 | 32,000 | 29,000 | 5,000 | 105,000 |
| UK | 633,000 | 894,000 | 54,000 | 454,000 | 622,000 | 854,000 | 51,000 | 507,000 | 570,000 | 715,000 | 49,000 | 701,000 |

Finally, the loss of *Sphagnum* cover and expansion of shrub cover on drying bogs will increase wildfire risks, representing a potential positive feedback whereby initial degradation and carbon loss leads to an intensified risk of further degradation and carbon loss under future higher temperature and lower summer rainfall regimes. It should be noted however that our model assumes lower susceptibility of blanket bogs to climate change impacts when they are in a near-natural or re-wetted condition. Any actions taken now to protect or restore bogs now should reduce their vulnerability to climate change in future. Restoring the UK's peatlands to reduce or offset GHG emissions now, for example all soils to be sustainably managed by 2030 (Defra 25YEP) would therefore have the additional benefit of reducing risk of climate change induced peatland degradation in future. Peatlands are a key measure in achieving the Government's net-zero target by 2050 e.g. to restore 50% of upland peat (CCC 2020). On the other hand, severe climate change could jeopardise the success of peat restoration measures, and thus make the achievement of net zero emissions more difficult.

We note that the predictions made here can be considered conservative compared with studies which suggest an 80% reduction of peatland habitat in the UK under 2 $^oC$ warming (Gallego-Sala & Prentice, 2013; Ferreto et al., 2019). Our more conservative approach recognises that blanket bogs occur in other warmer regions such as Spain, outside the apparent climate space of UK blanket bogs, as well as some dryer areas such as the Falkland Islands and Eastern Patagonia. Even where peatbogs start to fall out of the bioclimatic envelope, the bogs themselves are likely to persist in some form, albeit one that emits carbon rather than being an effective carbon sink.

Table 35 shows the impact of increased temperatures above the threshold on greenhouse gas emissions (as t $CO_2$ equivalent), taking into account current emissions from peatlands in four condition categories (see Table 30). At UK level, annual emissions increase from 3.5 million tonnes at baseline, by a further 104,000 tonnes under a 2 $^oC$ scenario and 501,000 tonnes under a 4 $^oC$ scenario. In England, annual emissions increase from 551,000 tonnes at baseline by a further 84,000 tonnes in both scenarios. In Wales, annual emissions increase from 80,000 tonnes at baseline, by a further 19,000 tonnes in both scenarios. In Scotland and in Northern Ireland, exceedance only happens under the 4 $^oC$ scenario. Scotland has the largest contribution to UK annual emissions, owing to its higher proportion of peatland area, and the relatively high proportion that is already degraded, increasing from 2.4 million tonnes at baseline by a further 372,000 tonnes. Annual emissions from Northern Ireland increase from 411,000 tonnes at baseline by a further 24,000 tonnes under a 4 $^oC$ scenario. The step changes in emissions are a consequence of the low and high severity levels used in this screening assessment. A more continuous impact is calculated in the case study.

These emissions have implications for UK commitments to reduce UK mainland carbon emissions under the Net Zero target; emissions from UK peatland soils have been estimated at 23 Mt $CO_2e\ yr^{-1}$ (Evans et al., 2017), which is around 4% of reported current UK greenhouse gas emissions (note that most peatland emissions are not currently included in this total, although the government has committed to include them within the next three years).

*Table 35. **Net GHG emissions from peatlands at baseline and under 2 °C and 4 °C scenarios (t $CO_2e$).** Estimates incorporate emissions from UK peatlands in current condition categories at baseline and projected change in emissions due to climate impacts. Figures rounded to nearest '000.*

| | Annual economic cost of $CO_2$e emissions (£) | | |
|---|---|---|---|
| | **Baseline** | **2 °C** | **4 °C** |
| England | 551,000 | 636,000 | 636,000 |
| Wales | 78,000 | 97,000 | 97,000 |
| Scotland | 2,480,000 | 2,480,000 | 2,853,000 |
| NI | 412,000 | 412,000 | 436,000 |
| **UK** | **3,521,000** | **3,625,000** | **4,022,000** |

### 7.3.4 Economic assessment – impact on goods and services

The assessment focuses on valuing the greenhouse gas emissions, since robust methods for quantifying the economic value of other ecosystem services linked to changes in peatland condition, such as biodiversity, and water quality and storage, currently do not exist (Martin-Ortega et al. 2014; Glenk et al. 2018).

The economic cost of emissions is calculated using the UK non-traded price of carbon[17], which reflects the cost of achieving the UK's carbon budget target. The future carbon price does not account for future changes in climate. Since future carbon price changes over time, we have to make some assumptions about the timing of impacts in order to derive a more robust valuation. Representative prices for non-traded carbon for these years are shown in Table 36 below. The cost of emissions is calculated by multiplying the CO2 equivalent emissions by the carbon price for that year.

*Table 36. Prices for non-traded carbon at relevant timescales for the national screening assessment*

| **Time period** | **2019** | **2031 (representing 2 °C)** | **2064 (representing 4 °C)** |
|---|---|---|---|
| Non-traded carbon value (2018 £/t$CO_2$e) | 68 | 88 | 328 |

The annual cost of GHG emissions at UK level is £239 million for the current state of peatlands (Table 37). This amount rises by around £100 million under the 2 °C scenario, amounting to annual emissions valued at £318 million by 2031. Although there is only a modest increase in greenhouse

[17] Valuation of Energy Use and Greenhouse Gas. Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government. Department for Business, Energy and Industrial Strategy. April 2019.

gas emissions of 3% due to threshold exceedance only occurring in areas of England and Wales, the value of emissions rises proportionally more. This is because the cost of greenhouse gas emissions increases over time as emissions targets become more stringent. By 2064 which corresponds to a 4 $^{o}$C scenario, the value of peatland emissions due to threshold exceedance increases markedly to £1,319 million. This increase in impacts is driven by two main factors. Firstly, projected temperature increases triggers nearly 400,000 $tCO_2e$ more emissions in Scotland, where the costs of emissions increase dramatically from £168 million to £935 million respectively. Secondly, the cost of emissions rises substantially by 2064 to £328 per $tCO_2e$, further reflecting stringent mitigation targets later in the century.

These result in two important risks associated with thresholds in UK peatlands. First, high temperatures risk triggering non-linear changes in greenhouse gas emissions from peatlands, which will contribute to the stock of gases already in the atmosphere. Second, unlocking these emissions later in the century would be costly in terms of the UK reaching emissions targets. Since these emissions would need to be offset in other parts of the economy where marginal abatement costs will be high, the increase in UK peatlands emissions due to exceedance of temperature thresholds represent a future risk to the ability of the UK to cost-effectively reduce greenhouse gas emissions.

The risk assessment conducted in CCRA2 (Section 3.7.1) does not quantify changes in greenhouse gas emissions driven by changes in UK climate. The analysis conducted here contributes new evidence that climate change presents a risk to the functioning of UK's natural assets and that this will subsequently affect the UK's ability to reduce its own emissions.

*Table 37.* ***Economic cost of GHG emissions at baseline and under 2 $^{o}$C and 4 $^{o}$C scenarios (£ million)***

| | Annual economic cost of GHG emissions (£ million) | | | Economic cost of additional GHG emissions compared with current day (£ million) | |
|---|---|---|---|---|---|
| | **Baseline** | **2 $^{o}$C** | **4 $^{o}$C** | **2 $^{o}$C** | **4 $^{o}$C** |
| England | 37.4 | 56.0 | 208.5 | 18.5 | 171.0 |
| Wales | 5.3 | 8.6 | 31.9 | 3.3 | 26.7 |
| Scotland | 168.7 | 218.3 | 935.8 | 49.6 | 767.0 |
| NI | 28.0 | 36.2 | 143.1 | 8.2 | 115.0 |
| Isle of Man | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 |
| **UK** | **239.4** | **319.0** | **1,319.3** | **79.6** | **1,079.9** |

### 7.3.5 Adaptation

For Chain 1 temperature effects, the analysis focuses on upland or lowland bog peatlands with the threshold indicated by a likely change in vegetation communities and ecological condition associated with a non-linear decline of Sphagnum mosses. The ability to withstand such changes is governed by the initial condition of the peatland; *'functioning peatlands are resilient ecosystems able to (up to a trigger point) withstand pressure for change'* (Gallego-Sala & Prentice, 2013). If the effect is absolute i.e. all peatlands cannot function under threshold high temperatures, there may be no adaptive response, but the evidence suggests that they will be more resilient to climatic pressures if they are in good condition, and may indeed be able to self-adapt (e.g. through changing their vegetation species mix) to continue functioning. This autonomous adaptation may nonetheless lead to a change in ecological condition (with significant vegetation change), or an adverse change in the amount and type of ecosystem services provided by the peatlands.

The priority adaptive response for both these potential impact pathways should be to raise water levels and to institute other management interventions (e.g. changes in grazing or burn management) that favour the survival or re-establishment of key peat-forming species, most notably *Sphagnum*, of a functional acrotelm, and of a resilient hummock-hollow topography. In the most extreme areas of degradation (e.g. active erosion gullies) more substantial interventions such as dam construction and active revegetation may be required. Further no/low regret action in the next five years is necessary to avoid irreversible damage and increased restoration costs in future. This should not rely on voluntary action by land managers. Suggested actions are included in Table 38.

However there are barriers to widespread implementation of measures such as rewetting as this currently relies on voluntary uptake of incentivised options e.g. through agri-environment schemes. Even those peatlands that are under some element of protection, e.g. SSSIs and SACs, are vulnerable; ECI (2013) estimated that only 35% of SSSI peatlands were in a "favourable" or "unfavourable recovering" condition.

NAP actions are:

- Maintain and expand current peatland restoration programmes in semi-natural habitat;
- Develop new sustainable management measures to ensure that the topsoil is retained for as long as possible and greenhouse gas emissions are reduced where peat cannot be restored;
- Publish an England Peat Strategy;
- Support and develop the evidence base for the sustainable management of agricultural peatlands;
- Improve the representation of peat soils in the greenhouse gas emissions inventory to enable the effectiveness of emission mitigation action to be tracked more accurately; and
- Continue to work with the horticultural industry to transition to peat alternatives.

There is also a target, mentioned within NAP 2, which reiterates the aspiration included in the Natural Environment White Paper (2011) and restated in the Defra 25 Year Environment Plan (2018), for all of England's soils to be managed sustainably by 2030. This target includes the end of peat use in horticultural products by 2030. The CCC report on policies for a Net Zero UK (2020) references a £10 million Peatland Grant which is being shared across four projects to restore over 6,000 hectares of lowland and upland peat in England. This is anticipated to deliver estimated annual savings of 23,000 $tCO_2e$. The Scottish Government has also awarded £8 million for restoration projects since 2012 under the Peatland ACTION project (CCC, 2020). The peatland restoration target within the CCC policies for a Net Zero UK report includes restoring 50% of upland peat and 25% of lowland peat. The cost of these restoration activities is estimated to be £1.6 billion for upland peat restoration and £0.3 billion for lowland peat restoration (CCC, 2020). In Scotland, there is a target to restore 50,000 hectares of degraded peatland by 2020, and 250,000 hectares by 2030 under the Scottish Government's Climate Change Plan (Scottish Government, 2018). Adaptation approaches are summarised in Table 38.

*Table 38. Adaptation approaches for temperature impacts on peatland carbon balance*

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Management interventions (e.g. reduced grazing and/or prescribed burning) | Relies on voluntary uptake of incentivised options, e.g. through agri-environment schemes. Only 35% of SSSI peatlands are in a "favourable" or "unfavourable recovering" condition (ECI 2013). The 25YEP has an intention to restore vulnerable peatlands (upland and lowland) by 2030 and restore 75% of terrestrial protected sites to favourable condition.<br><br>Managed burning should not be considered an effective form of climate change mitigation (Baird et al., 2019). | Local projects have made progress; for example MoorLIFE installed 4,000 dams, planted 200,000 plug plants, and laid 53km of geotextile material to prevent soil erosion (Moors for the future, 2015). The avoided carbon loss is estimated at 4.48 tonnes CO2e/ha/yr (Maskill et al, 2015). Around 110,000 ha of UK peatland have undergone some form of restoration between 1990 and 2013, of which 73,000 ha involved re-wetting (Evans et al., 2017) | **Delivering adaptation:**<br>Providing the skills and equipment are available, adaptation can be delivered by raising water tables and changing management of peatland.<br><u>Regulation</u>: Impacts of peatland degradation are mainly a public cost (e.g. reduction in water quality and increase in carbon emissions) and some actions can be mandatory under the polluter pays principles. Where prescribed burning is associated with economic activities such as grouse shooting, there is no economic case to stop burning and regulation would be required to stop this practice.<br><u>Advice</u>: Where land managers recognise the private and wider benefits of peat degradation, information and advice can change behaviours and drive effective autonomous adaptation.<br><u>Incentives</u>: Upfront capital investments are required for installing dams and raising the water table, so capital grants can incentivise infrastructure to manage degradation. Land managers may also be hesitant to take land out of agricultural production without incentives. The new environmental land management schemes in the UK post-Brexit provide a basis | **Delivering adaptation:**<br>Restoration is a process that can take decades. As time passes, and peat becomes more degraded, it becomes increasingly expensive to introduce adaptation actions to reverse or slow this damage. The risk of lock-in also means that early action is beneficial. Early restoration improves the potential of functioning peat to self-adapt to climate change, bringing further benefits (Paul Watkiss Associates, 2019).<br>Actions under ELMs, Tier 1 payment scheme include maintaining water levels in peat soils.<br><br>**Building capacity:**<br>Raising awareness within the next 5 years will bring benefits as without knowledge around this |
| Raise water level/ Dam construction | | | | |
| Maintain and expand current peatland | £10 million peatland grant scheme commenced in 2018 to deliver projects covering c.1% of peatland areas in | N.A – the percentage of upland bogs in favourable condition (SSSIs) has decreased | | |

| | | | | |
|---|---|---|---|---|
| restoration programmes in semi-natural habitat | England. The National Trust is also working to restore and manage peatlands (CCC, 2019). The UK Peatland Strategy, launched in 2018, aimed to restore 1 million hectares of degraded peatland by 2020 and 2 million hectares by 2040 (Paul Watkiss Associates, 2019). The Peatland Code also looks to increase private funding available to restore peatlands. The Scottish Government's Climate Change Plan aims to restore 50,000 hectares of degraded peatland by 2020, and 250,000 hectares by 2030. | from 19% in 2003 to 12% in 2018 (CCC, 2019). | for incentivising relevant change in land management.<br><br>**Building capacity:**<br>There is huge scope for improving awareness of future climate impacts and adaptation responses available regarding peatland. This needs to be targeted spatially and focused on the economic case as well as the public good aspect.<br>Technologies for reducing peatland degradation are widely available. However, capacity is currently limited by the availability of the contractor base for carrying out restoration. We need to grow this contractor base to increase the amount of restoration that can be carried out. Action is also dependent on incentives and practicalities.<br>Further research into paludiculture, rearing animals on wetted land, and other uses of peatland which can maintain productivity and store carbon simultaneously may be beneficial (Paul Watkiss Associates 2019). | topic, land managers may not readily take action. |
| Prevent soil erosion | The 25YEP aims to develop new sustainable management measures to ensure that the topsoil is retained for as long as possible.<br>Relies on commercial good practice or voluntary uptake of environmental land management schemes. | N.A | | |
| **Is risk managed by autonomous or planned adaptation?**<br>Planned adaptation will be required where incentives are needed to restore peatlands/prevent degradation as benefits are generally for the public good rather than the private good. Land use change may be associated with a loss of productivity (and therefore income), particularly in productive lowland peatlands; hence autonomous adaptation is unlikely in these situations. Mitigation can delay the threshold, however, once the threshold has been crossed and peatland has been removed or irreversibly damaged, no adaptation can be undertaken to rectify this. | | | | |
| **Risks of lock-in** | | | | |

| |
|---|
| Permanent and irreversible loss of peatland |
| **Risk(s) interacting**<br>Degradation of peatland leads to soil erosion and carbon emissions<br>Restoring peatlands/preventing degradation has positive impacts on biodiversity<br>Restoring peatlands/preventing degradation has a positive impact on water quality and helps regulate downstream flow |
| **Urgency scoring**<br>More urgent – more action needed. Action is needed to prevent irreversible damage. This would be a no and low regret adaptation. Restoring peatlands is both a mitigation and adaptation response. |

**What is the impact of current levels of adaptation at mitigating these risks?**

Local projects are making progress with efforts to maintain peatlands; around 110,000 ha of UK peatland are estimated to have undergone some form of restoration between 1990 and 2013, of which 73,000 ha involved re-wetting (Evans et al., 2017). Rates of peat restoration have increased since 2013 as a result of recent funding initiatives, notably the Scottish Government's Peatland Action programme and the Defra peat restoration fund, as well as a number of large peatland-focused EU LIFE projects. Despite this, the percentage of upland bogs in favourable condition has apparently decreased from 19% in 2003 to 12% in 2018 (CCC, 2019). However, it should be noted that this only relates to designated sites.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Up to a point, a functioning peatland which is in good condition will have some resilience to temperature change and drought impacts. Therefore, improving the condition of peatlands can reduce the impacts of reaching the threshold. Actions such as raising the water table, and management interventions such as changes in grazing and burn management, can be taken to reduce the loss of peatland. In the most extreme areas of degradation (e.g. active erosion gullies) more substantial interventions such as dam construction and active revegetation may be required. These actions could be taken in advance to reduce the risk of peatland being lost. However, as damage to peatlands is difficult and expensive to reverse at best, and may be irreversible at worst, adaptive management responses will be far more effective if they can be undertaken before climate thresholds have been crossed.

**In what scenarios are there limits to adaptation?**

Potentially irreversible degradation of peatlands can occur if peat dries out to the extent that it becomes hydrophobic, as the structurally altered peat will not re-wet. Gully erosion also presents a major challenge for peat restoration, because it fundamentally alters the topography and hydrology of peatlands, which form in areas of low relief over millennia. Once the threshold has been crossed, where peatland is currently degraded there is a risk of the peatland becoming irreversibly damaged, at which point no adaptation can be undertaken to rectify this.

Many adaptation actions are currently largely implemented through voluntary actions within agri-environment schemes, which can limit uptake. The Peatland Code highlights a number of restoration options. Measures such as raising the water table and constructing dams require a catchment approach, which may present coordination challenges.

# 8 Woodlands

## 8.1 Summary –Woodlands

This section covers all UK woodlands. The literature review identified three potential threshold-based impacts (section 16.4.1), of which two were taken forward in the national screening assessment. The assessment focused on managed woodland stands, and separate analysis was conducted for oak-dominated stands, other broadleaved woodland and coniferous woodland. The first impact relates to combined effects of drought and temperature (represented by climatic moisture deficit above threshold level), for which the assessment was conducted using forest growth models. The second impact relates to potential pest and disease impacts. It was not formally assessed, but adaptation approaches for this impact were explored. The case study (section 14) focused on the temperature and drought effects on woodland production in more detail.

*Drought and temperature effects on productivity of managed woodlands (Ne 7)*

Two climatic moisture deficit (CMD) thresholds were used to assess growth and timber quality in a range of commercial tree species: 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).

Forest growth models show impacts range from slight, moderate, and to severe, depending on tree species. Impacts on oak and beech are severe, along with other deciduous woodland species. Impacts on conifers are mixed. All impacts vary geographically and are greater in the south and east of the UK. In west and north Scotland, climate change will lead to increased growth for Sitka Spruce, but in eastern and southern Scotland more frequent drier summers will reduce growth and timber quality.

Current adaptation focuses on planting a more diverse range of species and in mixtures, selecting more tolerant provenances suited to climate change, and managing pest and pathogen outbreaks, which may be climate-mediated. Adaptation management planning in the forestry sector is slow. The conifer production sector in UK forestry relies on shorter crop rotation than the broadleaved woodland management sector and seems comfortable to risk abiotic and biotic damage to crops with an earlier/shorter felling intervention if necessary.

**Urgency scoring -** More urgent – more action needed. More action is needed on species selection for future climate-proofing, and developing or selecting genotypes better adapted to future climate stresses.

*Temperature influence on pests and pathogens (Ne 7, Ne 9)*

Warmer temperatures cause increased fecundity and voltinism (accelerating its life cycle stages) in invertebrate pest species. A warmer climate, particularly mild winters, encourage range expansion of tree pests and pathogens, leading to increased tree mortality, reduced timber quality and consequent impacts on economic production. The threshold varies depending on the pest or pathogen species.

Current adaptation focuses on preventing the introduction and establishment of new pest/disease organisms. However, the rate at which new pest/disease organisms have arrived in the UK has continued to increase. Future adaptation will generally be achieved through further monitoring including: new methodologies from technology to citizen science: increasing woodland resilience through moving to mixed species mixed age planting: and developing genomic tools to accelerate the production of resilient tree varieties.

**Urgency scoring -** More urgent – more action needed. The risk is currently low, but stress and disease/pest susceptibility, and therefore economic losses, will increase with wetter winters followed by more frequent hot dry spring and summer climates.

## 8.2 Overview: Managed woodlands – national screening assessment

This section covers all UK woodlands. The literature review identified three potential threshold-based impacts, of which two were taken forward in the national screening assessment. The screening assessment for this habitat focuses on managed productive woodland in Britain's forestry sector: oak woodland, other broadleaved woodlands, and conifer woodlands. The impacts prioritised in Table 39 represent an in-combination analysis of climate variables which have been assessed using forestry growth, timber quality and economic models in this assessment. The full list of potential impacts identified in the literature review can be found in Section 16.4.

*Table 39. **Potential threshold-driven impacts in woodlands***

| Climate-mediated stressor | Habitat | Threshold | Biophysical response | Ecosystem services affected | Aligned risk descriptors |
|---|---|---|---|---|---|
| Temperature, Rainfall | Woodland (Managed oak, other broadleaved and conifer woodland) | 3 years per decade with climatic moisture deficit (CMD)<br>>200 mm drought sensitive species<br>>300mm drought tolerant species; | Biotic tree stress, leaf loss, cambium cracks, growth reduction in following years, abiotic pest and pathogen infection | Carbon sequestration, timber quality | Ne 7 |
| Temperature | Woodland | Varies depending on pest & pathogen species | Biotic tree stress, leaf loss, growth reduction in following years, pest and pathogen infection | Carbon sequestration,<br>timber quality, | Ne 7, Ne 9 |

## 8.3 Temperature and drought effects on woodland

The thresholds and the assessment chain are summarised in Figure 16. Temperature and low precipitation together determine the drought indicator, climatic moisture deficit. Climatic moisture deficit is the maximum annual accumulated excess of potential evaporation over rainfall. We set a threshold of climatic moisture deficit of 300 mm which leads to seasonal water stress, reduced tree growth and, more importantly for standing crops where yields are less affected, poor timber quality due to shake (cracks in heartwood) that reduce timber value. The impact is lower yields, particularly from young plantations, and lower economic returns on sale of wood. The factors governing moisture stress are tree-species dependent, and also vary with soil type. More detailed analysis on this impact is covered in the case study, which incorporates a broader set of climate data.

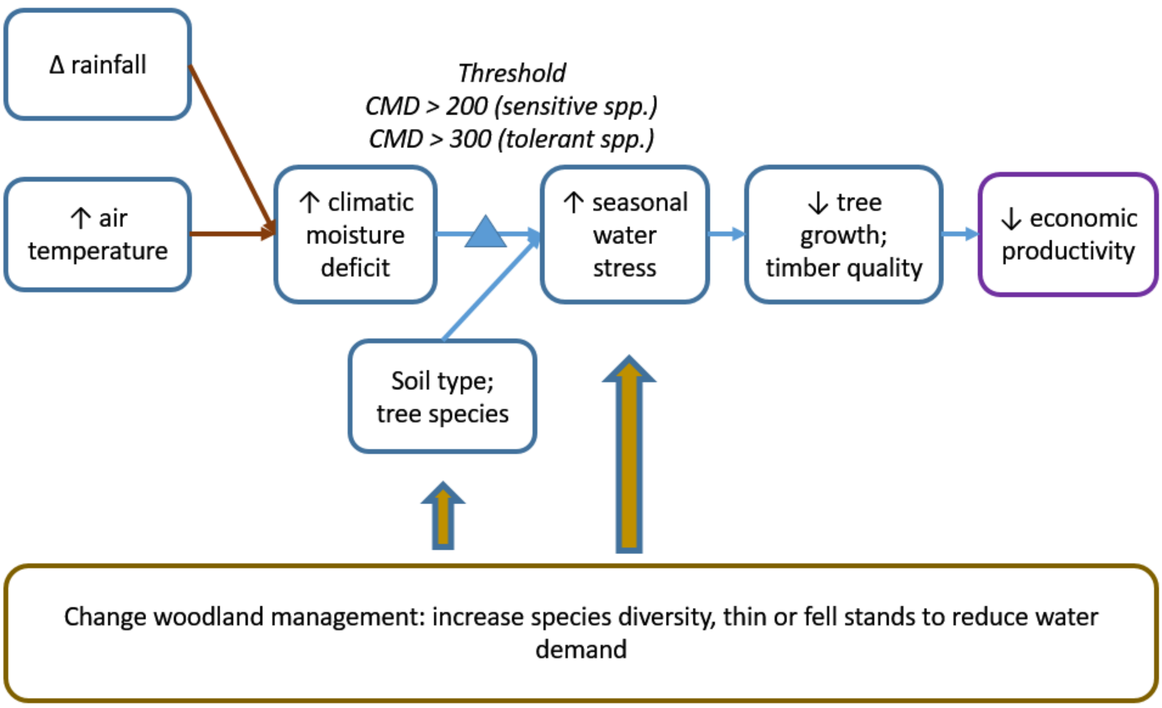


*Figure 16. **Impact chain showing the effect of increased temperature and summer drought on woodlands**. Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures*

### 8.3.1 Justification of threshold used in the assessment

This screening assessment focuses on the impacts of summer drought stress. The thresholds use a drought indicator from the Ecological Site Classification (ESC) - a forest site classification system (Pyatt et al,. 2001) - called the climatic moisture deficit (CMD) index that reflects the maximum accumulated monthly excess of evaporation ($Et_0$) over rainfall (P) each year. Threshold values of CMD for production vary according to the drought sensitivity of species. The pedunculate oak CMD threshold of 280 mm indicates the upper limit of sites classed as suitable for oak production.  Sitka spruce is less drought tolerant and has an upper CMD threshold of 180 mm, whereas the threshold for Scots pine is 260 mm. To simplify the assessment, we assumed a general tolerance threshold for drought sensitive species (200 mm) and relatively more drought tolerant species (300 mm), as the CMD thresholds likely to impact the timber production of managed forest stands.

In some regions oak woodlands are in decline and the valuable timber provided by oak stands is threatened due to reduced timber quality from abiotic stress such as late frost and summer drought. Areas affected by oak decline (OD) occur in the south and east of the UK, with a significant proportion of stands (~25%) on surface-water gley and ground-water gley soils. Climate change is thought to be a driver of the decline due to:

- much warmer and drier summers, which exacerbates summer drought stress. Warmer summers and drought combined cause a greater stress than the separate climatic impacts alone, in many species of tree (Allen et al., 2015); and
- small increases in winter seasonal rainfall, exacerbating periods of anaerobic conditions during waterlogging that reduces root health and rooting depth.

### 8.3.2 Impacts on natural assets and the services they provide

Climate change is now contributing to a proportion of oak trees showing signs of decline (Denman et al., 2014; Oosterbaan and Nabuurs, 1991) and associated mortality (Brown et al., 2016). Warmer drier summers as well as wetter winters and extreme winter cold can all cause shake (cracks in the tree stem) (Price, 2015; Savill et al., 1990), reduced canopy density (Brown et al. 2016) in some woodlands, parks and other open situations.

Many tree species subjected to abiotic stress, such as extreme warmth and drought, extreme frost, or waterlogging, succumb to secondary biotic impacts of pests (Ramsfield et al., 2016; Seidl et al., 2017) and/or pathogens (Thomas et al., 2002). In combination, these impacts affect the growth rate of trees, and the wood quality. The former influences the time to harvest, impacting revenue, and the rate at which carbon is sequestered. The latter governs the end point of harvested wood, e.g. whether it can be used for veneer, planks, or just for pulp. Both affect the economic value of harvested wood.

### 8.3.3 Ecosystem assessment – climate hazard thresholds

Above the threshold CMD of 200 mm for drought sensitive species and 300 mm for species more tolerant of drought, the impacts on tree growth rates and wood quality begin to occur.
The interaction of abiotic and biotic impacts of climate change on tree species normally causes a reduction in the annual growth in younger trees. This is often the result of xylem embolism[18], the impacts of which can last for several years following the stress (Bigler et al., 2007, 2006). A further impact is the damage to the quality of the wood which is often only apparent when the tree is harvested (Price, 2015).

The screening assessment for woodland was only conducted for one climate projection, consistent with a 2 °C scenario, and reports impacts for 2050. Some extrapolation is made from these outputs to provide a narrative for possible effects under a 4 °C scenario. This differs from the approach used in the other screening assessments, and is due to the use of forestry models to conduct the assessment.

[18] Blockage of a water conducting pathway in a vascular plant by an air bubble; cause by dissolved air coming out of solution under extreme tension

The degree of impact varies according to species, and phenotypic variation (differences caused by site and microsite characteristics on a genotype, and genotype x environment interactions) within a species. Individual trees (and other organisms) are a product (phenotypes) of both the genetic code present in DNA (the genotype) and the stimulus of the environment. Genotype interactions with environment lead to phenotypic variation in characteristics of individuals of the same species. In this report, based on thresholds used within the models, we calculate the magnitude of predicted change in species suitability under climate change together with the site types vulnerable to greater seasonal changes in the soil water regime to estimate the proportion of oak, broadleaved and conifer woodland that will be exposed to lower timber quality under climate change.

Our estimates use the published standing volumes of different species across age classes according to the regions of the National Forest Inventory (NFI) of Great Britain (Figure 17). Northern Ireland is not included in this woodlands assessment.


*Figure 17. Location of the National Forest Inventory (NFI) Regions*

The standing volumes of different species (NFI, 2013) described by the sample square data of Britain's National Forest Inventory (NFI) according to the regions of the NFI are used in a forest production model. The most mature age classes of broadleaved trees will have passed the point of maximum mean annual increment (MMAI) and therefore an assumption is made that the impact of climate change on mature stands of oak and broadleaved yield will be small between 2020-2050. A yield reduction was applied to conifer stands of 80-100% of current yield based on the ESC model, with the spatial variation of yield impacted by climate change severity according to NFI region. For all three woodland types we assume that the impact of climate change (extreme years) on tree stress causing wood structural damage and biotic impacts could be large affecting wood quality, compared to the small losses in yield. Therefore, the model adjusts the assortment of wood products according to the degree of climate change exposure in each NFI region. The method follows the work of Tubby (pers comm), providing economic data on the value of the oak timber resulting from the product assortment likely from thinned or felled oak stands. The product assortment was adjusted to reflect the changing proportion of stems of low, medium and high quality according to the proportion of stands on shake and dieback susceptible soil types (surface-water gley soils) by NFI region as climate change is projected to progress. Broadleaved woodlands and conifer woodlands were assessed in a similar way. For conifer stands we made an additional adjustment to the rate of growth based on ESC. Due to the shorter rotations of conifers their maximum rate of growth (maximum mean annual increment) would occur during the period 2020 to 2050.

We assume a linear exposure gradient of climate change from 50% in 2020 to 100% in 2050, under the equivalent of the RCP8.5 emissions scenario (approximately associated with reaching a 2 ˚C scenario in 2050). We have used two standard thinning interventions on the older age class volumes of timber (over 80 years old) of 33% of the volume respectively in 2030 and in 2040, and we model the felling of the remaining 34% in 2050. The size of stands in which thinning or felling is modelled has been set at 10ha for oak and broadleaves leaving remaining areas as refuges for biodiversity.

### Impacts on selected tree species and interpretation of reduced timber quality

The growth/damage risk classes relate to the frequency with which the climate threshold is exceeded in a ten-year period, and therefore the magnitude of impact on different species. The growth/damage classes are slight (S), moderate (M) and severe (X), as shown in Table 40.

A growth/damage risk class of "slight" may reduce the growth increment in the dry year with unusually warm summer periods in one or two years per decade. This would impact forest ecosystem services by reducing: biomass (lower carbon sequestration and timber production). Increasing the risk of *Elatobium abietinum* (green spruce aphid) outbreak (Straw et al., 2005) and defoliation in spruce and pine forest. Increasing the risk of powdery mildew (Dantec et al., 2015) on broadleaved trees (particularly oak) in the one or two years following the drought.

*Table 40. **Projected drought risk to nine commercial tree species for a 2 °C RCP4.5 scenario in 2050 compared to 1981-2010 baseline climate for 14 UK regions**. Damage/growth reduction risk classes: S=Slight, M=Moderate, X=Severe.*

| NFI Region | Current mean summer temp degC | Change in mean summer precip % | Change mean summer temp degC | Picea sitchensis | Pinus sylvestris | Pseudotsuga menzeisii | Tsuga heterophylla | Quercus robur | Quercus petraea | Fagus sylvatica | Acer pseudoplatanus | Betula pendula |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North West England | 15 | -15% | 2.4 | M | M | S | S | S | M | S | S | M |
| North East England | 14 | -15% | 2.3 | M | M | M | X | M | M | S | S | M |
| Yorkshire and Humber | 15 | -15% | 2.6 | X | M | M | X | M | M | M | M | M |
| East Midlands | 15 | -25% | 2.7 | X | M | M | X | X | M | M | M | M |
| East England | 15.5 | -25% | 2.9 | X | M | M | X | X | M | X | M | M |
| South East England & London | 16.5 | -25% | 3.1 | X | M | M | X | X | X | X | X | M |
| South West England | 15.5 | -20% | 2.8 | M | M | S | M | S | S | S | S | S |
| West Midlands | 15 | -20% | 1.7 | X | M | S | M | M | M | S | S | M |
| North Scotland | 12 | -5% | 1.9 | S | S | S | S | S | S | S | S | S |
| North East Scotland | 12 | -15% | 1.9 | M | S | S | S | S | S | S | S | S |
| East Scotland | 13 | -15% | 1.9 | M | S | S | S | S | S | S | S | S |
| South Scotland | 13.5 | -15% | 2 | S | S | S | S | S | S | S | S | S |
| West Scotland | 13.5 | -10% | 2 | S | S | S | S | S | S | S | S | S |
| Wales | 15 | -20% | 2.5 | M | M | S | S | S | S | S | S | S |

A damage class of “moderate” would similarly reduce the growth increment in the warm and dry summer conditions occurring in two years per decade, causing the bark and cambium of a small proportion of susceptible trees to crack (Green and Ray, 2009; Price, 2015). The cracks would reduce the timber quality in conifers and broadleaved species; in broadleaved species it would reduce the market value of the wood. It is difficult to estimate the reduced value, as prices vary with species. The cracking of 20% of Sitka spruce stems would reduce the value of the saw-mill quality wood but have a lesser effect on pulp or fire wood. Oak is particularly prone to cracks in the tree stem - ‘shake’ - in dry summers on silty and loamy clay textured soils (Price, 2015). Within the stem of trees suffering star shake and/or ring shake, cracks occur reducing the high timber value of oak to a lesser firewood value. Other broadleaved and coniferous trees can also suffer shake. Shake in oak reduces the value of the timber, particularly from wetter winters followed by dry summers.

A damage class of “severe” might occur when two or three (or more) very dry summers occur sequentially or are interspersed in a decade, for example 2-3 extreme hot and dry summers in a decade. The drought conditions may cause rapid decline and senescence of a proportion of trees in a woodland stand (e.g. ~20%). Drought of this severity would cause leaf loss and shoot dieback, fungal and bacterial infections, and in extreme cases bleeds from xylem embolism (Urli et al., 2013) as tracheid cells cavitate reducing the water flow for transpiration to occur. Recent studies have placed tree species on an isohydric – anisohydric gradient referring to the degree of stomatal control tree species exert, which is related to the likelihood of embolism (Roman et al. 2015). The framework has the potential to provide the means of improving tree choice in relation to soil types and current/forecast climatic conditions (Martinez-Vilalta et al. (2014) also contains placements on the gradient for 102 tree species) In addition to reduced productivity and biomass production, the dead and dying trees would be liable to collapse. In publicly accessible woodlands and along roadsides this would present a public hazard and would be expensive to manage. Increasingly, very dry spring weather has increased the likelihood of fire in some parts of Britain. Forest fires in western Scotland and in the western Pennines have occurred frequently since 2010. The fire risk to forest stands is likely to increase as a result of climate change. Biodiversity would be severely affected with a rapid increase in deadwood species and reductions in facultative (e.g. mycorrhizal fungi) and obligate species (Mitchell et al., 2019).

Climate change is expected to cause a shift in seasonal climates across Britain. The climate projections show that under a future 2 $^0$C warming scenario, drier, warmer summer, and wetter winter conditions will become the norm. The change in climate may slightly reduce the carbon sequestration function of woodlands. This is more likely in the south of England (Ray et al., 2010), but may be offset in the next 30 years by an increased woodland carbon sink in north western England and western Scotland (Ray, 2008). In the east and south of Scotland, and in north east and east England a reduction in the carbon sink is likely. Under 4 $^0$C warming scenario a reduction in the woodland carbon sink is likely in Britain as a result of extreme heat and drought events damaging forests (Allen et al., 2015; Hanewinkel et al., 2012; Seidl et al., 2017). Below is a list of selected species with comments on the likely effects of increasingly drier and warmer summers, and the carbon sequestration impact of climate change:

- Sitka spruce (*Picea sitchensis*) is a major commercial forest tree in the UK. Normally, it is not commercially planted on sites where the total annual rainfall is less than about 1200 mm per year. This limits the tree to regions north and west of a line between the Bristol Channel and the River Tees. Within this spruce zone there will be a change in risk of drought damage from slight to moderate in Wales, North West England, North East England, Northern Ireland, and Eastern Scotland. Indeed, Sitka spruce was badly affected on shallow soils of steep slopes in eastern Scotland in the 2003 drought (Green and Ray, 2009). Sitka spruce is confined to wetter climatic sites, so the species should remain a net carbon sink. In south and west Scotland warmer growing conditions and low drought risk will promote growth and carbon sequestration in Sitka spruce stands.

- Scots pine (*Pinus sylvestris*) will become increasingly prone to moderate drought damage under a 2 ˚C scenario, even in the uplands of England, Wales, Northern England and regions of Scotland. Dothistroma needle blight is a major pathogen of Scots pine, and projected climate change in Scotland will reduce growth and carbon sequestration in Scots pine stands (Ray *et al*, 2017). Similar impacts will occur in North England, and Wales.
- Douglas-fir (*Psuedotsuga menziesii*) is considered a drought tolerant species, however the 2 ˚C scenario climate in England will cause a moderate risk of drought damage. Work is underway to select more resistant genotypes of Douglas-fir from progeny trials, and also select phenotypes exhibiting greater plasticity to drought conditions (B4est – H2020 project, 2018). In the wetter climates of south west England, Wales, and Scotland, Douglas-fir woodland should remain a net carbon sink.
- Western hemlock (*Tsuga heterophylla*) was once considered a 'forest weed' of no value due to its shade tolerance and capacity to regenerate in commercial woodlands. It has a minor role as a timber species in Britain. However recent interest in this shade tolerant trait has led to wider acceptance of the species to diversify woodlands. It is quite drought sensitive and would be prone to severe risk of drought damage in England, leading to reduced growth and reductions in carbon sequestration in affected stands.
- Oak (*Quercus robur* and *Q. petraea*) are both widely used species in commercial broadleaved woodlands being valuable timber species, and both are currently affected by die-back (Thomas *et al*, 2002; Denman *et al*, 2014) that may be connected with a shift in seasonal weather patterns. Oak dieback is widespread in Europe and is thought to result from changes in seasonal weather patterns as a result of climate change. Indeed growing season drought produces climate stress in oak across its range (Drobyshev et al., 2008). In Britain, oak has gradually increased as a proportion of mixed woodland. More pure oak managed woodland now occurs than in previous centuries. However, pure oak woods are not naturally occurring and the species may need to be reduced as a proportion of broadleaved woodlands under the effects of climate change.
- European beech (*Fagus sylvatica*) was badly affected by the drought years of 1976 and 2003 in the south of England (Mountford and Peterken, 2003). Recent work (Hacket-Pain et al., 2016) suggests that provenances of beech across southern England may be particularly sensitive to drier summers. This would cause a reduction in the growth and carbon sequestration of beech woodlands in the south of England.
- Common sycamore (*Acer pseudoplatanus*) has become more widespread in UK woodlands, but is relatively drought sensitive, leading to a potential risk of moderate drought damage in parts of England and a slight risk of damage in Scotland, Wales and Northern Ireland. This could lead to a reduction in tree growth and the carbon sequestration of sycamore stands in England.
- Silver birch (*Betula pendula*) occurs on drier heathland sites in Eastern England and South East England, where it is likely to be moderately affected by drought under climate change projected under a 2 ˚C scenario. Birch is a major broadleaved species in Scotland. This could lead to a reduction in tree growth and the carbon sequestration of birch stands in England and Wales, but less so in Scotland.

The effect of the changing mean climate varies spatially across Britain and the effects vary among different tree species. As summers become warmer and drier in the south of England many species of tree will reduce biomass production from little change in some species to a 50% reduction for species that are sensitive to a dry climate (e.g. western hemlock). The main production conifer species (e.g. Sitka Spruce, Scots pine, Douglas-fir) are generally suited to current site types. Sitka spruce production is not possible in the south and east of England – except for some areas of the south-west. Sitka spruce production in north and west in Britain is predicted to be less severely impacted, and in the shorter term (to 2050) in the north and west will take advantage of warmer summers and increase biomass. Even so, the stochastic nature of extreme drought will always be present, particularly in north-eastern regions of Britain, and despite projected increases in yields, the drought damage risk and associated wood quality impact remains. Scots pine production is largely concentrated in the drier eastern parts of northern Britain and in East Anglia, and some forest stands in the south of Britain (e.g. New Forest). Climate change is likely to start to limit Scots pine production in more southerly areas, certainly after 2050s. Oak is concentrated in England and particularly the south. Oak management may be affected by wetter winters and drier summers on imperfectly draining soil types, where shake (Price, 2015) occurs and could become more serious. European beech was badly affected by the 1975-76 drought, following which stands of trees suffered severe dieback in the New Forest over the following two decades (Mountford and Peterken 2003).

### 8.3.4 Economic assessment – impact on goods and services

No further economic analysis is reported on this impact.

### 8.3.5 Adaptation

Various silvicultural system responses to adapt stands to drought stress could be considered (see Table 41). An option for drought stressed stands of trees on dry sites (in summer) would be to reduce the density and basal area of the stand. This would reduce the competition for water in dry summer conditions. As a rule, woodlands managed for timber are thinned at regular intervals to reduce light competition for the best selected final crop trees (Kerr et al., 2011). Adaptation management might increase the thinning frequency and/or the proportion of the stand removed. This also comes at a cost, particularly for stands in which the tree species produce epicormic branching in response to light. Epicormic shoots which are left to grow produce new branches on the bole of the stem. This is the most valuable part of the tree for timber production, and epicormic branching can reduce the proportion of high quality veneer and planks in oak. Similarly, for other species, over-thinning a stand often encourages heavier branching with an effect of reducing the value of wood from the stand. Average costs of moving to continuous cover forestry (CCR) are estimated at £1,800 per ha (Davies & Kerr, 2011).

We estimate the projected economic impact of climate change on conifer wood quality in the UK to be less severe. This is because Sitka spruce, Scots pine and other conifers are regularly planted on upland site types less prone to the severe warmth and drought (in western uplands for spruce, and central and eastern uplands for pine) than broadleaved trees in the lowlands (Petr et al., 2014). However, under a 4 °C scenario (not explored in this analysis) the yield reduction of conifers could be 20% (Petr et al., 2014). Adaptation approaches are summarised in Table 41.

*Table 41.* ***Adaptation approaches for temperature and drought stress in forest management***

<table>
<tr><th>Nature of adaptation</th><th>Current status & plans</th><th>Benefits of adaptation</th><th>Potential further action or investigation</th><th>Case for action in the next 5 years</th></tr>
<tr><td>Increase frequency of thinning interventions</td><td>Relies on voluntary uptake or through agreed forest management plans with a (devolved country) forest management grant scheme. There is a huge volume of unmanaged or undermanaged timber in the UK (Silva Foundation, 2017)</td><td>Reduce competition for water resources on drier sites. Promote natural regeneration on nutritionally poor sites (increase natural selection)</td><td rowspan="3">Delivering adaptation: Forest adaptation will take decades. Forest managers will be reluctant to intervene earlier in the rotation of forest management systems.<br><br>Building capacity: Forest management is a slow business, and change can occur only gradually. This is due to the limits of resource available to owners/managers</td><td rowspan="3">Delivering adaptation: Adaptation management must start now for commercial softwood and hardwood production. The time lag towards an adaptation management focused more resilient forest resource will take 50 years for softwoods and 120 years for hardwoods. So action in 5 years should be continual</td></tr>
<tr><td>Following the felling of forest stands, determine suitable replacement species for the site conditions under climate change</td><td>This involves discussing plans with the country forest authority office. Owners/agents and woodland officers can use the forest classification system (ESC) to better understand the options for woodland species on the site under climate change (Pyatt et al., 2001)</td><td>Improved site-species choice appropriate to future climate projections</td></tr>
<tr><td>Encourage mixed species (diversification) through natural regeneration after thinning or by planting different species</td><td>The diversification of stands reduces intra-specific competition. Mixing upper- and lower-canopy species helps reduce soil and woodland floor temperature extremes – reducing evaporation (Morecroft et al., 1998).<br>Mixed species stands have been shown to more resistant to invertebrate defoliation (Jactel et al., 2017) and more productive (Jucker et al., 2014).</td><td>Improved resilience of forest stands through diversification and ecosystem function</td></tr>
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| | | | | |
|---|---|---|---|---|
| Reduce the stand density and basal area to reduce competition for water | Reducing stand density will reduce competition for water (Ford et al., 2017) but alter other micro-climate factors such as light and soil temperature. Therefore, thinning should be done a little and often, and so interventions will be more expensive over the rotation. | Reduce competition for resources | and forest operations contractors. There is still much inertia in forest management due to lack of awareness of the increasing vulnerability of many forest stands and management systems. Raising awareness will bring benefits, but the pace of change will be slow because of the resource limitations. | adaptation action over 150 years.<br><br>**Building capacity:** Petition the commercial private forestry sector to build resilience into their woodlands. Resilience is and should not simply focus on the commercial perspective. |
| Continuous cover forestry systems (CCF) | CCF provides more even microclimatic conditions. This occurs when the forest canopy is maintained through continuous thinning. Restocking glades after thinning can be through planting or natural regeneration. The system will promote more equitable microclimate for tree establishment compared to clearfelled stands. Other ecosystem service benefits include maintaining biodiversity, maintaining soil nutrients, reducing soil loss, reducing soil water evaporation, stabilizing slopes, preventing soil compaction (Seedre et al., 2018). Maintaining more continuous woodland habitat should be encouraged through incentives. On particularly sensitive woodland sites with thin soils and southerly aspects, there is a danger that complete harvesting of woodland will render the site difficult to restore to woodland. | Maintain cooler woodland conditions in woodland glades for the establishment of cohorts | | |

**Is risk managed by reactive or planned adaptation?**

Forest management is long-term and adaptive, with relatively little scope for reactive adaptation given the lifetime of even fast-growing tree species. Incentives will be required to hasten forest adaptation and help secure more resilient woodlands that will help mitigate rising greenhouse gas emissions. Many broadleaved woodlands have been under-managed for decades, and this has caused overstocking and high competition for resources for growth in woodland stands. Oak in woodlands has increased over the centuries because of its higher value, and the oak component of many oak woodlands should be reduced by mixing other broadleaved and conifer species. Conifer woods tend to be more intensively managed on shorter rotations and in pure stands. There should be incentives to promote mixtures, to reduce the risk of pest and pathogen impacts in single species, uniform age plantations.

**Risks of lock-in**

| |
|---|
| There are high risks associated with selection of tree species for future climates, or management decisions on thinning taken currently due to the long life-time and extended management cycles inherent in managed woodland. Choosing the wrong species now, or implementing the wrong management regimes may affect future climate resilience. |
| **Risk(s) interacting**<br>There are interactions between abiotic and biotic impacts that together increase the likelihood of worsening woodland health.<br>Fire also poses an increasing risk of loss to woodland. Woodlands at risk in dry spring and summer climates and where access is encouraged should have prominent warnings about the danger to people and the woodland habitat. |
| **Urgency scoring**<br>More urgent – more action needed. The risk of woodland loss is currently low, but loss will increase with, as projected, more frequent hot dry spring and summer climates. |

**What is the impact of current levels of adaptation at mitigating these risks?**

The forestry sector is very slow to respond to the issues of climate change. The public sector is perhaps more engaged in adaptation management planning. This takes the form of checking species suitability in future climates using Ecological Site Classification (Pyatt et al., 2001) and provenance trials (Field et al. 2019), adjusting species choice and making more use of mixed species woodland in planning. The private sector appears to be less concerned as Sitka spruce is better situated in the north and west of Britain where the consequences of abiotic damage are projected to be less pronounced. Biotic damage from pests and pathogens is the main concern in production forestry. Current research in the UK and Europe is focusing on adaptive traits and phenotypic plasticity to select tree genotypes that are better suited to the future climate.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

In woodland management, the view is typically long-term and management is adaptive. Early felling and replacement, and mixed species coupes are the most likely options to enhanced climate resilient stands. There are more options for new plantations and restocking. The selection and use of more tolerant tree species and mixed woodland types to increased frequency and duration droughts, warmer temperatures, but also water-logging during winter months, in the future, will be required. Testing the progeny of British provenances in trials to select better adapted tree lineages would greatly help the selection of material for resilient woodlands. Research in areas of assisted diversification and building genetic resources will improve the ability to provide seed material a wider range of phenotypic variance and tolerance to future conditions within native species. Fundamentally, however, a better matching of species requirements to the correct habitat and site conditions will be essential for future planting schemes to make woodlands more resilient.

**In what scenarios are there limits to adaptation?**

Alternative tree species for commercial planting are potentially available, for any climate conditions, but it will take time to replace existing stock. Acceptance by foresters to adopt these species for planting, and acceptance by timber users of different products may limit the success of adaptation.

## 8.4 Temperature influence on pests and pathogens

Figure 18 below summarises the threshold and assessment of increased temperatures on pests and pathogens. Warmer temperatures allow pests and pathogens to increase their life cycles faster and expand their range, leading to increased tree mortality, reduced timber quality and consequent impacts on economic production.

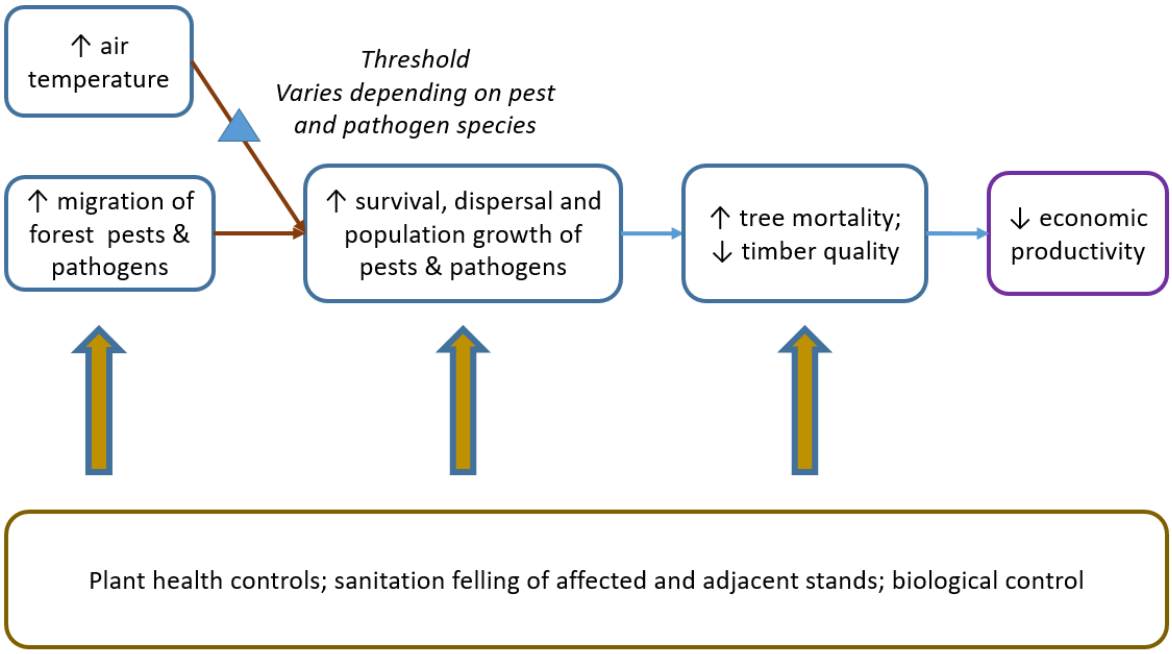


*Figure 18. **Impact chain on temperature effects for fecund pest or virulent pathogens**. Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures.*

### 8.4.1 Justification of threshold used in the assessment

While this report focuses on the impacts of abiotic-biotic related climate change impacts on forests and forest trees, it should be recognised that some pests and possibly pathogens show strong responses to change in the climate. Examples include the scolytoid pest European Spruce Beetle *Ips typographus* attacking wind damaged and weakened trees, first recorded in the UK in 2018, but increasingly likely to spread beyond current distribution boundaries (Seidl & Rammer 2017). A meta-analysis of drought related biotic tree damage suggests trunk associated damage will decrease, but leaf and root related damage will increase with drought pressure (Jactel et al. 2012). The damage of secondary agents such as the fungal genus Armellaria, including *A. mellea* (honey fungus) also increase with drought stress severity.

Following the *Temperature Summation Rule*, some insect pests are particularly temperature sensitive and an increase in warmth can affect voltinism, overwintering mortalities and flight behaviours (Candolle 1855; Bentz and Mountain, 2016). Others might change their geographic range, but with no further change in their biology. An example of an insect pest changing its biology is the impact of the European Spruce Beetle, *Ips typographus*, in recent years on the European continent, which has caused increasing damage to large areas of Norway Spruce. *Ips typographus* is one of few well studied species; e.g. 144 degree days after 1$^{st}$ of April for one generation (Baier et al., 2007; Bentz & Jönsson, 2015), and models have been developed to assess outbreak risks (Baier et al., 2007). However, stochastic impacts cannot be easily incorporated into the modelling approach at present.

### 8.4.2 Impacts on natural assets and the services they provide

A review by Damos & Savopoulou – Soultani (2012) demonstrates that temperature accumulation rules are often species-specific and can range from linear to non-linear responses (Damos and Savopoulou-Soultani, 2012). Pest and pathogen impacts can increase tree mortality, sometimes catastrophically and at a large scale, and negatively affect wood quality. Both can considerably influence the economics of timber production, not only for reduced yield and production in the longer-term, but in relation to increased management costs associated with pest and pathogen outbreaks.

### 8.4.3 Ecosystem assessment – climate hazard thresholds; and economic assessment – impact on goods and services

No ecosystem or economic assessments for pests have been conducted in this analysis, but could be explored for future work. Climate hazard thresholds for pest/disease organisms are generally not well known, and where there are examples from elsewhere in the species range, e.g. European Spruce Beetle, thresholds are idiosyncratic to pest and disease organisms. While there are a number of positive correlates of population parameters and climate change related factors, namely temperature and development time, and diapausing, survival (undergoing a period of suspended development) to increase voltinism, there are also potential negative impacts for instance from heat waves or thermal shocks, and indirect impacts through natural enemies. The complex interplay between abiotic stressors, trees and natural enemies means no general assessment particularly of hazard thresholds has been made to date (Jactel et al 2019).

### 8.4.4 Adaptation

Adapting trees, woodlands and forests to reduce the impacts of pests and pathogens is complex in that different pests and pathogens will have different dispersal and epidemiological characteristics. Considering pests in general, work on the impacts of defoliating invertebrates (Jactel et al., 2017, 2012; Ramsfield et al., 2016) has shown that the scale and severity of disturbance is reduced in stands that have increased tree diversity (mixed species stands). Mixed stands are often managed as continuous cover silvicultural systems, with the inherent advantages of small scale and frequent natural selection of a cohort that should be better adapted to the site type (climate and soil), based on natural selection processes. Growth benefits (overyielding) have been demonstrated in mixed stands (Mason and Connolly, 2020), compared to single species-single age stands. Also the wind firmness of wind sensitive stands (e.g. Sitka spruce) may be improved when planted in a self-thinning mixture on wet soils. Both of these benefits may provide an additional incentive for managing mixed species and multi-aged stands in the future. Adaptation approaches are summarised in Table 42.

*Table 42. **Adaptation approaches to temperature impacts on woodland pests and pathogens**.*

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Awareness and Horizon Scanning | Horizon scanning (HS) exercises try and predict emerging disease and introduced pests based on their current distributions, invasion histories, potential pathways and rank them by potential impact.<br>Among others, two horizon scanning exercises for invasive macro-organisms were carried out in 2013 and 2019 as expert opinion exercises by the Non-Native Species Secretariat (NNSS), although they were not forest pest focused, they picked up Emerald Ash Borer and Asian Chestnut Gallwasps (ACGW). One similar exercise aimed at micro organisms and | The NNSS exercises provided lists of priority species, although, due to the parameters given, forest pests were not part of the "top 10". However, there was awareness that *Dryocosmus kuriphilus* (ACGW) was likely to invade the UK and it did arrive in 2015. | **Delivering adaptation:**<br>Preparation can be conducted before pathogens enter the country. Project BRIGIT (https://www.jic.ac.uk/brigit/ ) is one such program and apart of the BBSRC Bacterial Plant Disease research programme, designed to prepare for the threat posed by Xylella bacteria to a wide range of plant species.<br><br>Detection of new introductions can be improved by new technologies employed at the point of entry. However, some new disease appears endemic to the UK and emerges sue to increasing stress on the trees. Thus increased monitoring by professionals, citizen science possibly guided by HS will improve chances of to have an early response.<br><br>In relation to mixed woodlands providing associational resistance this seems to apply at a range of levels from genetic to species diversity. However, there is scope for further | **Delivering adaptation:**<br>Adaptation management is likely to focus on an increase in mixed species, multi-aged woodlands. The commercial softwood forests should also be managed to encourage greater tree species diversity. Birch, alder, willow and other species enriching conifer woodlands will help develop resilient forest ecosystems with predators and defences against pests and diseases.<br><br>Tree breeding also has a major role in the protection of forests against pests and pathogens. Projects to test genotypes across environmental gradients in common gardens that study growth, resistance (pests and pathogens), avoidance (frost damage), to deliver increased forest resilience are desperately needed. Such trials would also inform the trade-offs involved in choosing material resistant to pest X but |

<table>
<tr><td></td><td>pathogens highlighted knowledge gaps. HS does not capture emerging diseases native to the UK.</td><td></td><td rowspan="3">research to optimise the effect by identifying most effective species combinations.<br><br>Some of the methods referred to under tree breeding (hybridisation, adaptive diversification, transgenic trees) might not be easily acceptable by the public. Trees and woodlands have a special status in the public conscience it would be important to take this into account if such methods are delivered at scale.<br><br>IPMs: Should the introduction of IPMs become more common establishing minimum standards to assess risk would be worthwhile. On individual cases ACRE would review and recommend measures. Should standards be established, templates are available for alien species or the plant risk register that could be adapted.<br><br>Building capacity:<br>Early detection in the field already builds on an FR advisory service and some Citizen Science initiatives. HS should be repeated at intervals and it stands to argue that a forestry focused exercise could be warranted. Methodologies should be reviewed.</td><td rowspan="3">which is less productive than phenotype Y.<br><br>Building capacity:<br>Decision support tools to help practitioners consider and recognise the potential risks from pests and pathogens. Tree Alert and the project Observatree have begun the process and should be extended to provide information about future high risk abiotic and biotic impacts.</td></tr>
<tr><td>Biosecurity regulation</td><td>As of 2019 regulations on the import of plants, wood and wood products has become more stringent restricting some species or the areas they can be imported from.<br>This combines with new technology to detect pests and disease at the point of entry (e.g. detection of pest and pathogens funded under the Tree Health and Plant Biosecurity Initiative (THAPBI)).<br>Most tree nurseries have a biosecurity policy.</td><td>Avoid the introduction of pests and pathogens at the borders and in the field. Should a recognised potential pest/disease be detected in the field an eradication protocol coordinated will be put in place.<br>For instance, Asian Longhorn beetle was detected in 2012 in Kent and eradication measures, felling, chipping and subsequent monitoring, were successful.</td></tr>
<tr><td>Silvicultural management</td><td>Current silvicultural practise varies widely reflecting different purposes from recreational woodland to timber production. The PuRpOsE (THAPBI) projects reports from a</td><td>We are not aware of any systematic assessment of the efficiency of alternative strategies relative to each other. There are numerous studies of individual</td></tr>
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| | forest manager's workshop involving all backgrounds. Common themes involved managing increasing climate pressure through use of improved provenances, increased species diversity, increased use of conifers ([https://protectouroaks.files.wordpress.com/2019/05/summary-report-of-tree-health-workshop-sept-2018.pdf](https://protectouroaks.files.wordpress.com/2019/05/summary-report-of-tree-health-workshop-sept-2018.pdf)) | strategies (Field et al 2019, in press). | Currently deployed we find web based questionnaires, Delphi style expert opinion elicitation and, although rarely in environmental science and not in pest/disease management, full expert opinion elicitation in a statistical framework to quantify uncertainties.<br><br>Inspections at the border are largely visual at this time, yet it is clear that some pathogens/pests are cryptic at certain life history stages or asymptomatic for visual signs in some host plants. | |
| Tree breeding and the of genomic resources | Selective tree breeding has been practised for many years. Beyond optimising existing forest species in the face of introduced pest/disease, the production of hybrids with species from the native range of the pest/disease is aimed to introduce resistance traits and less commonly practised in the UK (but see hybrid Larch progeny trials), | Selecting disease or pest resistant lineages or provenances within species is along established practise.<br><br>Hybridisation of *Castanea sativa* (European) and *C. crenata* (Asian) or *C. dentata* (American) and *C. crenata* have resulted in hybrids with resistance to chestnut blight (*Cryphonectria* | Recent research has emphasised a role of associational resistance, i.e. trees in diverse stands are likely to suffer less damage than in monoculture.<br><br>New genomic resources for various forestry species are rapidly becoming available. A large amount of work is necessary to apply such resources to improve tree species resistance and where more than one pest/disease is threatening additional challenges need addressing. However, applying such resources will make classic breeding and more intricate methods | |

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| | although such hybrids are available elsewhere). | *parasitica*) (Chira et al. 2018). Chestnut blight has recently recorded from the UK. However, success stories like this are rare and the creation and testing takes considerable time. Research in the US is also trailing a transgenic, resistant version of *C. dentata* | such as adaptive diversification more precise and quicker to deliver.<br><br>IPMs<br>There are currently no protocols (standard or specific) for the post release monitoring and the assessment of control efficiency. | |
| Integrated pest management (IPM) | IPM is a broad term and we think here foremost about the introduction of natural enemies of pest/disease to the UK. There is research into less harmful, more targeted and possibly natural product pesticides, but they development and deployment is tightly regulated.<br><br>The use of biocontrol agents for forestry pests is rare for the UK and comes with specific risks. | We are not aware of the use of biocontrol agents in forestry in the UK<br>On the European continent a parasitic wasp of ACGW, *Torymus sinensis* has been introduced widely supressing the pest populations successfully.<br>Cryphonectria hypovirus-I is being developed to control chestnut blight.<br>An application for the release of *T. sinensis* is being considered. | | |
| **Is risk managed by reactive or planned adaptation?** | | | | |

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| The statement on woodland health above largely applies to resilience to pest/disease. It is however important to consider woodlands with different functions, considering the ecosystem service benefits that individual woodlands provide. At one extreme are timber producing monocultures where the rigidity of one age cohort allows no reactive adaptation. The other extreme might be woodland for conservation and recreation, where natural selection processes could promote adaptation although the adaptive potential and the development of a woodland through transition is generally unknown. The genetic diversity in populations of particularly wind pollinated trees is characteristically high mainly due to potentially long pollen dispersal distances. Such high genetic diversity provides the potential for selection to change phenotypic profiles of woodlands including disease resilience. |
| **Risks of lock-in**<br>Risks of lock-in related directly to those listed for woodland health. A strong component of resilience in woodland trees is being in the right place and benefiting from optimal environmental conditions, such as water regime or soil type and chemistry. Changing abiotic conditions along a trajectory causing increasing stress means even with optimisation management decisions today will impact future susceptibility should new pests or disease arrive or arise. |
| **Risk(s) interacting**<br>The risks from pests and disease interact with abiotic factors such as climate change, but also other anthropogenic impacts where these increase tree stress and thus susceptibility. Of particular interest are also the direction and relative importance of potential pathways for pest/disease organisms, which will change over time. |
| **Urgency scoring**<br>More urgent – more action needed. Again linked to woodland condition as described above. The risk of woodland loss is currently low, but loss, and therefore stress and disease/pest susceptibility, will increase with more frequent hot dry spring and summer climates. |

**What is the impact of current levels of adaptation at mitigating these risks?**

As mentioned above, to date it is not clear for many pests or diseases whether threshold changes in relation to climate change would occur. Currently we expect them to arise where:

- Pests/diseases had previously restricted distributions, but climate change enables them to establish in the UK
- Tree condition changes in such a way that previously non-pathogenic, native organisms shift life histories to cause disease symptoms
- Climate change causes major changes in pest life-histories, e.g. voltinism, leading to a step-change increase in abundance and damage caused

Most adaptation management currently aims at interception and early detection to prevent the introduction and establishment of novel pest/disease organisms. Despite increased inspections at the point of entry and restricting import origin, the rate at which new pest/disease organisms have arrived in the UK has continued to increase reflecting increased international trade and in part industrial practice (more wood products as packaging material) (Harrower et al. 2018). Horizon scanning and Pest Risk Analyses allow the targeted use and development of interception methods (see UK Plant Health Register). Silvicultural methods and trials to identify resilience in individual species exist, and results should be more widely implemented. The genomic knowledgebase is increasing continuously, but applications, for instance in tree breeding programmes, need to develop before they have broad impacts.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Post establishment management of invading non-native organisms (INNOs) to the UK tends to depend on the epidemiology of the organism, but felling with the aim to remove or isolate the disease would be standard procedure. In some cases that involve disease vectors, management could target vector species rather than the disease directly (e.g. Xylella).

Managing tree condition has been discussed in the sections above. However, using the disease syndrome Acute Oak Decline as an example more research is needed for a functional understanding of environmental conditions and the susceptibility of the trees. According studies to-date they might involve managing soils in terms of nutrient input or drainage and planting strategies of future woodland.

Where pests or potential pests show changes in life histories in their ranges outside the UK, integrated pest management strategies could be developed potentially in partnership with international organisations before these changes occur in the UK. These could involve pheromone disruption or trapping strategies, but also natural enemies or entomopathogens.

**In what scenarios are there limits to adaptation?**

At this time, the main limit to adaptation is the lack of knowledge about physiological responses in pest/disease organisms and more so about population responses in their community settings, i.e. how the susceptibility of trees and control by natural enemies will develop, respectively.

The UK is very active in monitoring for likely new invasive species and their status as potential pests (Roy et al 2014). However, an equivalent exercise for pathogens identified knowledge gaps rather than a ranked list of organisms (Roy et al. 2017). For alien species entering the UK via classical invasions from other continents or by range expansions or movement under changing climates, the knowledge gaps would mostly be around control, or the lack thereof, in a community setting of native UK species. It should be noted that 60% or so of UK forests are in private ownership and there is no organised monitoring of impacts of pests and diseases, nor on silvicultural management and its ability to adapt to these impacts.

Considering the potential change in life-histories of species native to the UK the information predictions are mostly based on are again observations from warmer parts of their distributions on the European continent, see for instance PRA's in the UK Plant Health Register. This, however, does not take account of local or regional adaptation of trees affecting susceptibility, where well adapted trees in warmer European ranges can withstand higher pest/pathogen pressure, while trees showing higher stress levels might be impacted more if pressure from native pest/disease increases. Evidence that insect abundance responds to levels of adaptation or mal-adaptation to local environments comes from experimental trials with local and introduced provenances (e.g. Sinclair et al 2015, Field et al 2019). However, tree-herbivore relationships are complex and different feeding guilds of insects respond to different tree traits that are affected by for instance warming temperatures (Field et al 2019, unpublished data).

Monitoring potential pest and disease species abroad and within the UK will allow a focussing efforts and resources. Thresholds are likely not to be crossed throughout the range at the same time and in most case events will become apparent outside the UK range. However, additional research of the importance of tree and environmental factors that might differ across ranges, would significantly improve the ability to forecast future development in UK forests.

# 9 Marine and Coastal margins

## 9.1 Summary - Marine and Coastal margins

This section covers impacts in two NEA Broad Habitats: Marine and Coastal Margins. These have been combined because the pressures and impacts affecting these habitats are not always separated in the literature.

The literature review identified seven potential threshold-based impacts in marine and coastal systems (section 16.5.1), of which three were taken forward in the national screening assessment. Those impacts were: rising temperature effects on cod stocks, rising temperature on reproduction and spread of the Pacific oyster *Magallana gigas*, and coastal flooding impacts on residential properties. The case study focused in more detail on spread of the Pacific oyster.

*Temperature impacts on cod stocks (Ne 17)*

A sea-bottom temperature threshold of 12 °C defines the approximate distribution of cod. Above this temperature, recruitment and abundance of cod decline, leading to economic impacts on fisheries.

In the 2050s and 2080s, the analysis suggests that the area experiencing suitable temperatures for cod will change. The distribution of cod will decline in UK waters, becoming restricted to Scottish waters on the Atlantic; and will shift northwards in the North Sea.

No economic assessment was conducted due to uncertainty regarding the relationship between fish stocks, catch quotas and catches by UK vessels.

Current adaptation: In view of the existing pressures on cod stocks from the management of fishing grounds, planned adaptation is necessary to both protect the marine ecosystem and limit fishing, which should also anticipate future climate effects. However, this is likely to be contained within existing stringent management of North Sea stocks. Now that the UK has left the EU, it is no longer part of the EU Common Fisheries Policy (CFP)[19]. The UK Fisheries Bill will instead control management of fish stocks.

**Urgency scoring –** Less urgent – Sustain current action. UK decision-making is part of an international process.

*Temperature impacts on reproduction of the Pacific oyster Magallana gigas (Ne 17, Ne 18, Ne 19)*

825 degree days above a sea-bottom temperature of 10.55 °C defines the spawning threshold for the introduced Pacific oyster *M. gigas*. Above this threshold, *M. gigas* will successfully spawn, and establish new populations. Once established *M. gigas* is able to persist at lower temperatures. The main concern is for impacts on native ecosystems, with substantial negative impacts on a range of other intertidal and subtidal communities. From an ecosystem services perspective, impacts are mixed, with some positive impacts for water quality and potentially for coastal defence, but negative impacts on beach use, intertidal rocky habitats and mussel beds.

[19] https://ec.europa.eu/fisheries/cfp_en

*M. gigas* is currently farmed around UK coasts, but for much of the UK temperatures are too low for spawning (although this may vary depending on local conditions). The viable area for *M. gigas* spawning and reproduction increases from 47,000 km$^2$ at baseline, to 103,000 km$^2$ in the 2050s and 205,000 km$^2$ in the 2080s. The case study maps this range expansion. In the 2050s and 2080s, the suitable range for spawning spreads northwards from southern England into most UK coastal waters. It expands its mean viable settlement area by a factor of four in England, a factor of five in Wales, and introduces the potential for widespread expansion into Northern Ireland and Scotland for the first time.

Current adaptation: There is limited current adaptation. It is considered naturalised on the south coast of England, but there are few options for preventing its spread. Removal is costly. Farming can move to use of triploids to prevent spawning.

**Urgency scoring -** More urgent – Research priority - to assess the need and options for additional action.

## 9.2 Overview: Marine and Coastal margins – national screening assessment

The literature review identified seven potential threshold-based impacts in marine and coastal systems. Of those, two impacts were considered for development in the national screening assessment (Table 43). The full list of potential impacts identified in the literature review can be found in Section 16.5.

While threshold effects have been demonstrated in marine and coastal systems worldwide, there are relatively few in the UK or similar temperate waters. Two studies (Rocha et al. 2015; Osman et al. 2010) provide a general overview of literature on marine regimes in relation to drivers & impacts on ecosystem services. Rocha et al. (2015) reviewed the scientific literature for 13 types of marine regime shifts and used networks to conduct an analysis of co-occurrence of drivers & ecosystem service impacts. Climate change was one of the commonest co-occurring cause of regime shifts in marine ecosystems worldwide, with specified impacts including increasing temperatures, ocean acidification, and sea-level rise among others. Cultural services, biodiversity & primary production the commonest cluster of ecosystem services affected. However, assessment of 24 recent marine-related ecological resilience/regime shift publications (not restricted to UK temperate waters) showed no specific examples of ecological thresholds in relation to climate-driven threshold effects in UK temperate waters. A study by Spencer et al. (2011) tried to detect regime shifts in UK marine ecosystems by statistically examining long-term observational time series data for 5 biological components (fish, infaunal benthos, marine benthos, plankton & rocky shore invertebrates) from 7 marine regions around the UK. The analysis tended to suggest that trends in UK marine communities were dominated by gradual change rather than sudden shifts. Recent work has concluded on impacts on other fin-fish, for example the Climefish project used IPCC climate change scenarios to model the possible impacts on the mixed demersal fishery in the west of Scotland, highlighting changes in abundance and distribution of a number of species. These data were not available at the time of review.

*Table 43.* ***Potential threshold-driven impacts in Marine and Coastal margins.***

| Climate-mediated stressor | Habitat | Threshold | Biophysical response | Societal end-point affected | Aligned risk descriptors |
|---|---|---|---|---|---|
| Temperature | Marine | Bottom temperature of 12 °C | Altered growth & recruitment of cod; Change in Oxygen concentration | Fisheries (Cod) | Ne 17 |
| Temperature | Marine | 825 degree days above bottom temperature of 10.55 °C | Changes at species and community level (Oyster *M. gigas*) | Shellfisheries, biodiversity | Ne 17, Ne 18, Ne 19 |

## 9.3 Temperature impacts on cod fisheries

Figure 19 summarises the threshold and assessment chain. A sea bottom temperature above 12 °C will lead to reduced cod abundance, or shifts in the range of cod away from UK waters, which may lead to reduced cod catches in some UK fishing areas. A summary of the evidence behind the choice of threshold is provided in the following section.

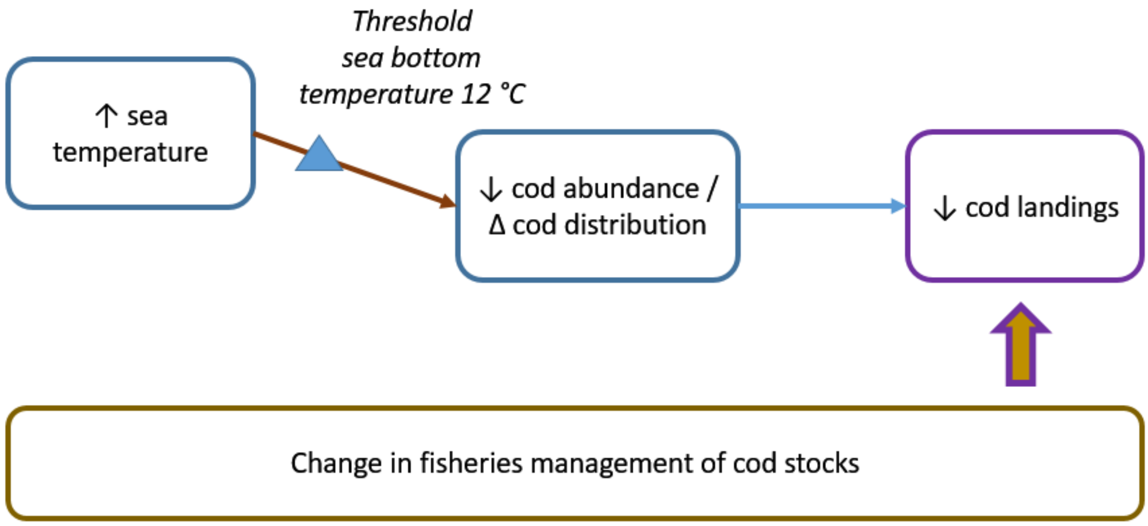



*Figure 19. **Impact chain for temperature effects on cod fisheries**. Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures*

### 9.3.1 Justification of threshold used in the assessment

The threshold temperature used for assessing cod distribution is an annual average sea bottom temperature of 12 °C. This is acknowledged as a proxy measure which broadly encompasses a multitude of environmental factors which affect cod distributions (excluding direct human pressures such as fishing effort and impacts on food chains). The evidence base underlying this choice of threshold is discussed below.

Shifts in cod distribution aligned to temperature change have been observed (Drinkwater, 2005; Engelhard et al. 2014), or modelled (Núñez-Riboni et al. 2019; Voss et al. 2019) in a number of studies, and this assessment follows a similar approach. However, the relationship between cod distribution and temperature is highly complex, reviewed in Drinkwater (2005). Cod are primarily found where annual mean bottom temperatures are 12 °C or less (Dutil and Brander, 2003). Recruitment has a more complex relationship with sea bottom temperatures. Analysis of Atlantic cod stocks shows that recruitment tends to increase with temperature up to a bottom-temperature of 6 °C, is more-or-less stable at bottom temperatures of 7-8 °C and declines at bottom temperatures above 8 °C (Drinkwater 2005). In an analysis of the North Sea cod stocks, those most relevant to a UK assessment, Clark et al. (2003) estimated a 30% decrease in recruitment with the highest level of sea surface temperature increase (0.026°C, annual mean). Other studies have suggested that a sea surface temperature (SST) above 9-10$^{o}$C can cause rapid ecosystem shifts, when taking into account oxygen concentration. Reductions in oxygen concentration below 6.45-6.60 mg/L$^{-1}$ in the North Sea caused changes in upper ocean chlorophyll, Calanoid mean size and diversity, and Cod occurrence (Beaugrand, et al., 2008), and other studies have shown that cod fitness in the Baltic Sea was negatively impacted by oxygen reduction linked to SST (Hinrichsen, et al., 2011). Brown, et al., (2016) predicted that by 2100 cod populations in the Irish and Celtic Sea could completely disappear due to climate change. While experimental evidence suggests that the ability of cod to extract oxygen from seawater is maximized at around 12°C (Colosimo et al. 2003), electronic tags have demonstrated that adult cod in UK waters inhabit a wide range of bottom temperatures (monthly average range 5 - 17°C; Neat et al., 2015) and those subject to the highest temperatures do not move to find cooler temperatures (Neat and Righton, 2007). Cod movements have been studied extensively and it is clear that the scale of movement in all life-stages is far less than the size of the International Council for the Exploration of the Sea (ICES) stock areas (e.g. for the North Sea see Neat et al., 2015; Wright et al., 2018). As a consequence, seasonal temperature exposure appears to be more closely linked to the region they inhabit, e.g. cod in the southern North Sea are exposed to the largest annual range where monthly bottom temperature often exceeds 12°C while those in the deep north east never experience this temperature. There is still considerable scientific debate as to how temperature and climate change is impacting cod recruitment and behaviour. Temperature effects on sensitive life-stages are likely to be more relevant to defining an unsuitable thermal environment. While there have been many studies that have correlated temperature and North Sea cod recruitment (O'Brien et al., 2001; Nicolas et al., 2014; Akimova et al., 2016), the precise mechanisms operating are still not clear. There is some evidence of avoidance of high temperatures by spawning cod, since they rarely spawn in temperatures >8°C (Righton et al., 2010; Gonzalez-Irusta and Wright, 2016). An experiment by Van Der Meeren and Ivannikov (2006) found that temperatures exceeding 9.6°C harmed the development of cod larvae. Temperature may also affect the synchrony between cod spawning and zooplankton production. Huebert et al. (2018) found that the growth rate of larval cod could be food-limited around the peak hatch time, and that in-turn this was correlated with subsequent recruitment strength.

### 9.3.2 Impacts on natural assets and the services they provide

Where bottom temperature exceeds the threshold, cod will decline in the south leading to a net shift in distribution northwards, or to areas which remain within favourable temperatures, with implications for UK fisheries.

### 9.3.3 Ecosystem assessment – climate hazard thresholds

In the analysis, the period 2000-2019 is used as the present-day baseline period. The temperature data was bias corrected against the NWS Ocean Reanalysis data (same resolution) using a reference period of 2000-2019. Climate data for the assessment of impacts on cod followed the approach used in the case studies, i.e. assessment against climatic conditions at baseline (2000 -2019), the 2050s (2040-2059) and the 2080s (2070-2089). Section 16.5 explains how the climate data for the marine assessment were sourced and used.

*Sea-sea surface temperature and bottom temperatures were mapped for UK waters (*

*Figure 20a). This indicates how cod distributions are likely to change from current day through to the 2050s and 2080s under a 4 °C scenario. The 12 °C isotherm of sea surface temperatures shows that this shifts northwards considerably, while the bottom temperatures (*

Figure 20b) also shift northwards. Thus the climate space for cod becomes restricted to Scottish waters in the Atlantic and Scottish and northern parts of English waters in the North Sea, where waters are deeper, and temperature does not exceed the threshold.

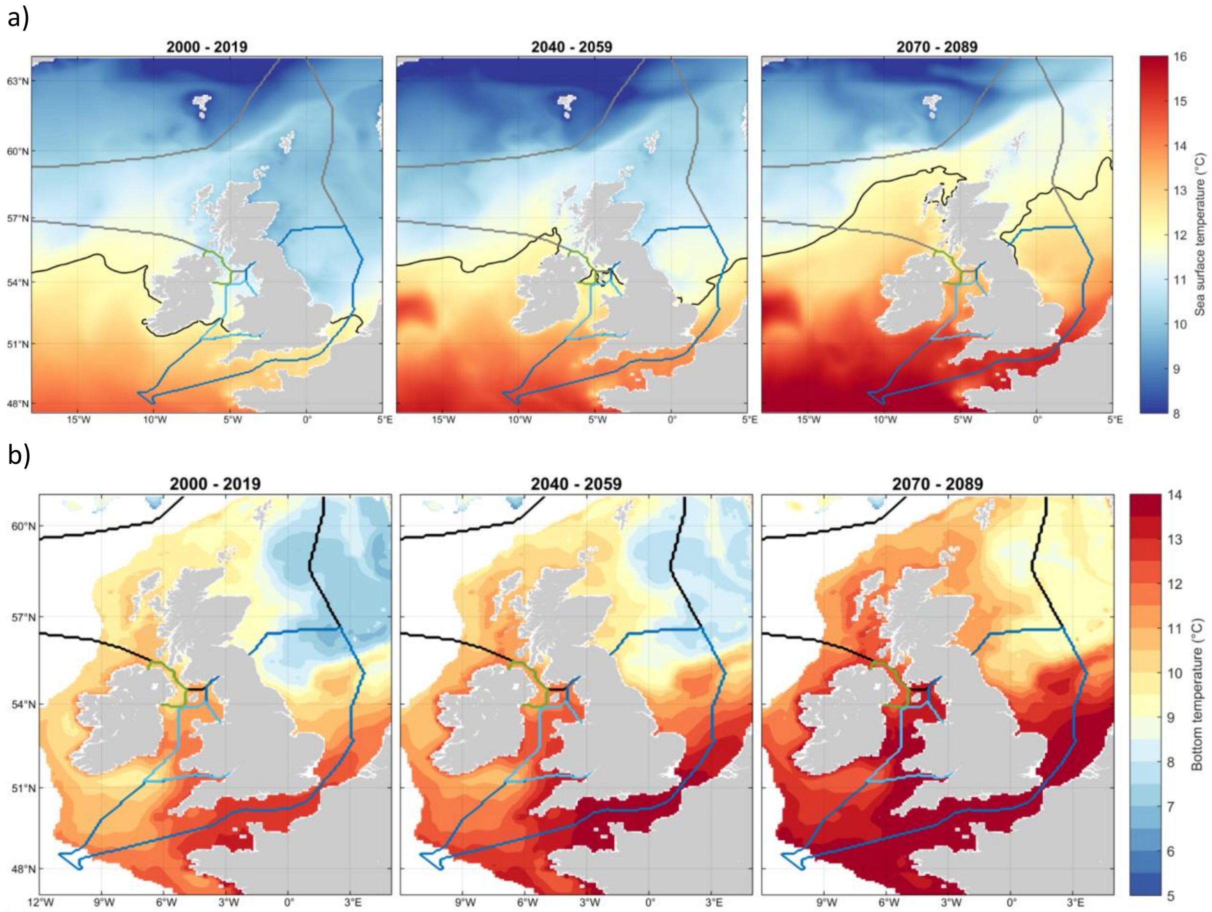



*Figure 20.* ***Sea temperatures around UK under 4 °C warming trajectory, for three time periods: baseline (2000-2019), 2050s and 2080s****. Data show a) sea-surface temperatures with 12 °C isotherm and b) bottom-temperature, shown to 350m depth. Thick lines show outer extent of offshore planning regions for each country.*

### 9.3.4 Economic assessment – impact on goods and services

No economic assessment was conducted due to uncertainty regarding the relationship between fish stocks and catches by UK vessels. The imposition of catch quotas also makes a robust assessment of the economic consequences of a northwards shift in cod difficult to quantify.

*Although the effects of shifts in cod population due to climate change on the UK cannot be estimated, it is possible to contextualise these potential impacts by examined how much cod is worth to UK fisherman currently. UK vessels landed 21,600 tonnes of cod into the UK in 2017, which had a value of £48 million, approximately 12% of the total value of UK finfish landings in that year (Elliott & Holden, 2018). Of this, £42 million of landings were from vessels in Scotland and £6 million was landed by vessels in England. Most UK cod landings in 2017 were from the north east and north west North Sea in areas where average temperatures are predicted to remain below 12 °C through to 2089 (based on*

Figure 20). Therefore, the southern North Sea cod have already declined, although it is not yet clear what the relative contributions of climate and fishing pressure were to this decline.

### 9.3.5 Adaptation

Adaptation options are summarised in Table 44.

**What is the impact of current levels of adaptation at mitigating these risks?**

In the first NAP, Defra committed to protecting and restoring marine habitats to increase their resilience to climate change. This action was led by the designation of Marine Protected Areas (MPAs) and utilising conservation zones as a network of habitats to aid the movement of species affected by climate change and decrease threats such as over-fishing. However, the design of MPAs only has limited consideration of climate change impacts. Whilst the Marine and Coastal Access Act (2009) sets out requirements for Marine Plans to take risks from climate change into account, to date, it is not clear what specific actions will be included within these plans and if the long-terms risks from climate change will be addressed. More generally, the plans lack detail on the type of risk assessed, the level of temperature rise and timeframe covered, and do not include clear actions. Within Scottish waters it is the Scottish Government who has competence to manage fishing activity and is considering its own approach towards adaption.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Most practical adaptation options are already undertaken as part of sustainably managed fisheries, for example regular assessment of cod stocks and managing fisheries accordingly. Area restrictions on fisheries, such as closed areas may be of benefit where cod aggregate and where this behaviour increases their accessibility to fishing. However, closures in areas where cod have already declined may not lead to a local recovery (Clarke et al., 2015).

**In what scenarios are there limits to adaptation?**

If managed sustainably, the fishery should be able to adapt to changes in stocks, although this may lead to reductions in quotas and landings, where necessary to conserve stocks in the longer term.

Regarding quotas, now that the UK has left the EU, it is no longer part of the EU Common Fisheries Policy (CFP)[19]. While quotas are set at international negotiations in which the UK will participate, the UK Fisheries Bill will instead control management of fish stocks. Within the Fisheries Bill, Defra intends to discuss with the Devolved Administrations, Crown Dependencies and stakeholders any additional fishing opportunities agreed from December 2020 onwards (at time of writing), using zonal attachment methodologies to allocate quotas (Defra, 2018). The policies implemented under this regulation will have an influence on stock levels and the ability to adapt to warmer sea temperatures.

*Table 44. **Adaptation approaches for temperature impacts on cod stocks**.*

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Designation of Marine Protected Areas | The area of marine protected sites has risen by almost 69% to 1.7 million hectares in the five years to 2018; although limited information is available on the condition of these (CCC, 2019). The proportion of designated coastal habits in favourable condition is around 60% (CCC, 2019). | N/A | **Delivering adaptation:**<br>The precautionary principle should apply, with actions undertaken on the basis of available information, while also advancing, strengthening and deepening the associated knowledge base.<br><br>**Building capacity:**<br>Expanding the coverage of MPAs will extend their role in delivering ecological resilience. Networks of MPAs respond better to climate change and other stressors when effectively managed e.g. assessment of ecosystem vulnerability to climate change, the reduction of anthropogenic pressures affecting adaptation capacity, and the implementation of new management options (Simard *et al.,* 2016). | **Delivering adaptation:**<br>Based on the precautionary principle, taking action within the next 5 years will reduce the risk of damage to cod stocks. |
| Sustainable exploitation of existing cod stocks | Certification to the MSC Fisheries Standard[20] allows product to be sold with the blue MSC label. The standard addresses sustainable fish stocks, minimising environmental impact and effective fisheries management. | N/A | | |
| Relocation of fisheries | Not currently widely practiced. | N/A | | |
| **Is risk managed by autonomous or planned adaptation?** In view of the existing pressures on cod stocks from fishing and climate and the management of fishing grounds, planned adaptation is necessary to both protect the marine ecosystem and limit fishing. This should anticipate future climate effects, including the natural movement of fish as seas warm. | | | | |

[20] https://www.msc.org/uk/what-we-are-doing/our-approach/what-is-sustainable-fishing

| |
|---|
| |
| **Risks of lock-in**<br>There is low risk of lock in as both designation of MPAs and adjustments to fishing regulations can be adjusted over time as needed. In the meantime, action should enhance ecological resilience. |
| **Risk(s) interacting**<br>None |
| **Urgency scoring**<br>Less urgent – Sustain current action. The North Sea cod fishery is highly managed at EU level. Although quota management is not perfect, recent declines in cod stocks have prompted more critical evaluation of the process. UK decision-making is part of an international process. |

## *9.4* Temperature effects on naturalisation of the Pacific oyster *Magallana gigas*

Figure 21 summarises the threshold and assessment chain for naturalisation of the Pacific oyster, *Magallana gigas* (previously *Crassostrea*) in the United Kingdom. Although legally cultivated, wild Pacific Oysters are classified as an invasive non-native species in the UK (Herbert et al., 2012). Above a threshold of 825 degree days in excess of 10.55 °C (bottom temperature), this leads to increased spawning and subsequent settlement. Moreover, *M. gigas'* optimal (sea bottom) temperature for growth is 20 – 25 °C. Therefore, rising water temperatures will lead to faster growth and an expansion of its current range. More detailed assessment of this impact is provided in a case study, which maps the change in viable spawning and reproduction area for this species over time.

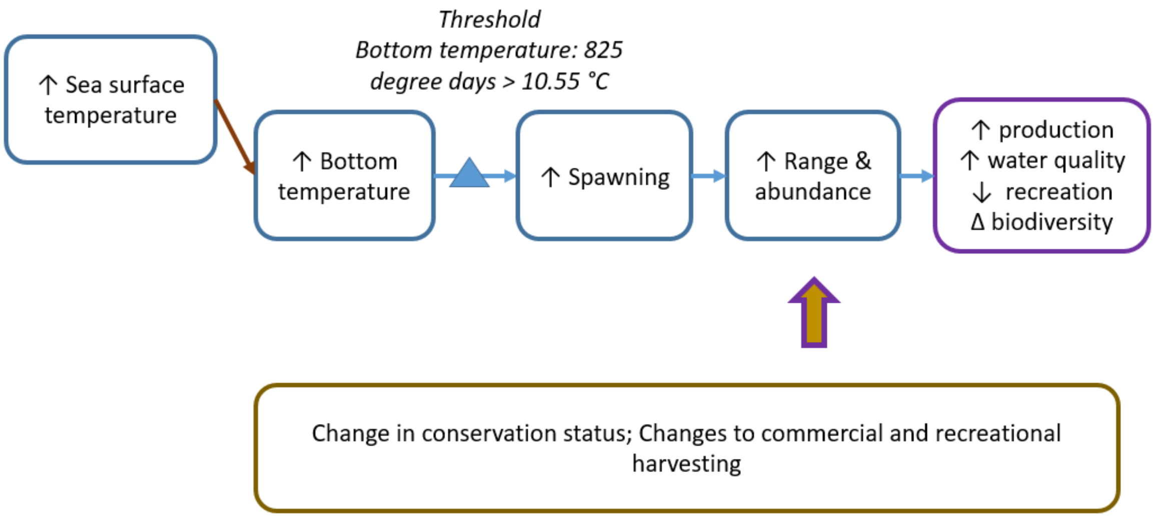



*Figure 21.* ***Impact chain for temperature effects on naturalisation of the Pacific oyster, Magallana gigas****. Purple box shows social/economic or biodiversity endpoint. Brown box shows potential adaptation measures.*

### 9.4.1 Justification of threshold used in the assessment

The threshold for spawning of *M. gigas* is 825 degree days for a daily mean bottom temperature of 10.55 °C. Past an initiation threshold, ectotherm growth and development increases linearly with temperature. Therefore, the time period needed to achieve a given development stage will vary depending on the experienced temperatures of an individual, and as such, development is best estimated in a cumulative stepwise manner based on daily temperatures experienced. This can be quantified by measuring "degree days". For *M. gigas*, Mann (1979) determined a biological zero ($T_0$) of 10.55 °C below which gametogenesis will not occur and a minimum number of 600 degree days above this to induce spawning. Recruitment is dependent on larvae developing and settling out of the water column which requires further degree days. Syvret et al., (2008) determined that an additional 225 degree days are required for settlement to occur. Here, we therefore base the risk of wild settlement to be a product of a total of 825 (600 for spawning and 225 for settlement) degree days above 10.55 °C.

### 9.4.2 Impacts on natural assets and the services they provide

Pacific oyster *M. gigas* is widely used as a farmed species in the UK. It was introduced to the NE Atlantic under the premise that water temperatures were suitable for growth but too cold for successful completion of its life cycle, and as such, naturalisation was not expected. Recent warming trends have changed this (e.g. Spencer et al., 1994). Summer temperatures in much of continental Europe now facilitate spawning and settlement and wild *M. gigas* populations can be found in areas far away from aquaculture sites. Currently, *M. gigas's* naturalisation frontier is along England's SE coast where it can be found in high abundances forming extensive reefs (Thomas et al., 2016). Changes to spawning are unlikely to affect farmed oysters directly, although increased temperatures may increase growth rates. There will be impacts on other services provided by this species where it spreads, including loss of services from habitats or species affected by its spread.

### 9.4.3 Ecosystem assessment – climate hazard thresholds

In the analysis, the period 2000-2019 is used as the present-day baseline period. The temperature data was bias corrected against the NWS Ocean Reanalysis data (same resolution) using a reference period of 2000-2019. Climate data for the assessment of impacts on Pacific oyster followed the approach used in the case studies, i.e. assessment against climatic conditions at baseline (2000 -2019), the 2050s (2040-2059) and the 2080s (2070-2089). Section 16.5 explains how the climate data for the marine assessment were sourced and used.

We determined the proportion of years where these settlement thresholds are exceeded for the baseline, and the following time periods (2040 — 2059) and (2070 — 2089). We also quantified the total viable area where thresholds are exceeded up to 2100. We limited all quantifications of suitable habitat and area to 50 m that represents the maximum depth for *M. gigas.*

UK seawater temperatures are predicted to rise considerably over the coming decades (Table 45). On average, temperatures at the seabed are estimated to increase by 0.9 °C by 2040 – 2049 and 2.0 °C by 2070 – 2089 in UK waters, with the largest increases taking place in the coastal waters of England and Wales, although all parts of the UK are affected by the 2080s. These temperature increases will result in settlement thresholds being exceeded at higher latitudes towards the end of the century resulting in a northward shift of the potential settling grounds of *M. gigas*. Increased temperatures will also push *M. gigas* towards its growth optimum of 20 - 25 °C bottom temperatures (King, 1977; Brown and Hartwick, 1988; Shpigiel and Blaylock, 1991). Therefore, there will be direct impacts on farmed oysters and the wider ecosystem impacted by wild settlement.

*Table 45.* ***Anomaly in bottom temperature (°C) (down to 50 m water depth) for 2050s and 2080s compared with baseline period (2000 - 2019), under RCP8.5.*** *Values in square brackets denote range with +/- 1 standard deviation over the time period.*

| Area | 2040 – 2059 | 2070-2089 |
|---|---|---|
| England | 1.0 [0.4; 1.6] | 2.3 [1.8; 2.7] |
| Wales | 0.9 [0.4; 1.5] | 2.2 [1.7; 2.7] |
| Scotland | 0.6 [0.1; 1.1] | 1.7 [1.3; 2.0] |
| Northern Ireland | 0.7 [0.2; 1.3] | 1.8 [1.4; 2.3] |
| **UK** | **0.9 [0.3; 1.4]** | **2.0 [1.6; 2.4]** |

### 9.4.4 Economic assessment – impact on goods and services

#### Expansion of settlement conditions

No economic assessment was conducted for this impact, but we present an analysis of likely range expansion for this species, and discuss the implications for native species and habitats, and ecosystem services which might be affected by expansion of *M. gigas*.

Over the baseline period (2000 – 2019) settlement thresholds were regularly exceeded as far north as Cardigan Bay in Wales and the Wash estuary in England. Infrequent exceedance was observed as far north as the Solway Firth in Scotland. Taken as a whole, this represents a 331 % increase in suitable settlement area for the UK (Table 46). Greatest gains in suitable area were observed in England, which was driven predominantly by large areas of the shallow North Sea around Dogger Bank. Scotland saw the largest percentage increase in suitable area, driven by large increases in suitable habitat in the Inner Hebrides.

*Table 46.* ***Mean viable area for oyster spawning and settlement for baseline (2000 – 2019), 2050s and 2080s, under RCP8.5 ('000 km²).*** *Percentage change (compared to 2000 — 2019) are shown in brackets.*

| | **2000 - 2019** | **2040 - 2059** | **2070 – 2089** |
|---|---|---|---|
| England | 42.8 | 89.7 | 167 |
| Wales | 4.7 | 12.2 | 25.8 |
| Scotland | 0.2 | 2.1 | 11.7 |
| Northern Ireland | 0 | 0.1 | 1.7 |
| **UK** | **47.5** | **103.9 (118 %)** | **205 (333 %)** |

The greatest concerns for *M. gigas* naturalisation have been the potential for conflict with native species and habitats. *M. gigas* can have adverse impacts on a range of habitats including mussel-beds (Kochmann et al., 2008), marshes (Escapa et al., 2004), rocky shores (Krassoi et al., 2008), seagrass beds (Wagner et al., 2012), polychaete reefs (Dubois et al., 2006) and mud flats (Trimble et al., 2009). Whilst the resulting effect on overall biodiversity levels is not always negative the shift in community structure can impact native food webs and trophic dynamics. The biggest concern for regional biodiversity is habitat homogenisation. As an ecosystem engineer *M. gigas* can completely transform intertidal systems and reduce habitat heterogeneity across different substrates. For example, there are extensive reefs of over 26.5 ha in The Netherlands (Fey et al., 2010). This may be a particular concern where there is the potential for spread of *M. gigas* into protected habitats. For example, intertidal rocky reefs and mudflats are Annex 1 habitats listed in the EU Habitats Directive and transformation may compromise their designation status. The greatest concern for impacts on individual species has been with native bivalves such as mussels, cockles and the native oyster. The blue mussel, *Mytilus edulis*, supports large fishery and mariculture enterprises in the UK (16,000 tonnes in 2017 (FAO statistics[21]), and *M. gigas* can almost completely replace it, reaching densities of up to 2000 per $m^2$ (Markert et al., 2013). Moreover, *M. gigas* can reduce the local carrying capacity for nearby cultivated mussels (Wijsman et al., 2008), by competing for food resources in the water

[21] http://www.fao.org/fishery/statistics/software/fishstatj/en

column. More recently, there have been concerns over competition with the native oyster, *Ostrea edulis* (Zwerschke et al., 2018), which is the focus of substantial restoration effort across Europe. Pacific oyster expansion can negatively impact some bird species such as Dunlin, red knot, common gull and oystercatcher which prefer mussels as a food source (Waser et al. 2016).

Whilst the majority of impacts of *M. gigas* on native species in the UK are negative, there is recognition that *M. gigas* can have both positive and negative impacts on ecosystem services (listed in Table 47). Positive benefits include improving water quality, some potential for improved wave attenuation with benefits for coastal defence, and the potential to harvest them for food. Negative impacts include reduced amenity value of beaches due to sharp shells on reefs causing a hazard to swimmers, surfers and other beach users, as well as indirect effects on production of other bivalves discussed above.

*Table 47.* **Positive (↑) and negative (↓) effects of M. gigas naturalisation on ecosystem goods and services**

| Regulating services | Provisioning services (direct & indirect impacts) | Cultural services |
|---|---|---|
| ↑ Improve water quality (nutrients, pollution, pathogens) | ↑ Potential for wild spat collection | ↑ Improve tourism through hand picking |
| ↑ Buffers coastal erosion | ↑ Opportunity for emerging wild fishery | ↓ Sharp shells may pose risk to beach users |
| | ↑ Trophic subsidiaries for fish and shellfish | |
| | ↑Nursery ground for commercial species | |
| | ↓Reduce carrying capacity for farmed bivalves | |
| | ↓ Smother native bivalve reefs (e.g. blue mussel, *Mytilus edulis*) | |

### 9.4.5 Adaptation

Adaptation options are summarised in Table 48.

In England, there are several NAP actions around marine plans and climate change in aquaculture, although none specific to oyster populations. Warming of seawater has led to the northwards spread of non-native species in the UK, including the Pacific Oyster (Scottish Association for Marine Science, 2015). More general NAP actions include:

- The preparation of ten new Marine Plans for the whole of the English marine area which will include horizon scanning to evaluate the potential longer term risks and opportunities from climate change
- Continue to establish Marine Conservation Zones to contribute to an ecologically coherent network of Marine Protected Areas
- Continue to support the Marine Climate Change Impacts partnership
- Continue to collaborate with selected marine sectors through the 'climate smart' working initiative to develop adaptive capacity
- Seafish will publish a climate change adaptation report describing the steps industry (fisheries and aquaculture) are taking to respond to climate change, focussing on risks and opportunities associated with climate change in the UK aquaculture sector

There are also several NAP actions around raising awareness of, managing, and eradicating non-native invasive species, but again, these are not specific to *M. gigas*.

The only proactive strategy to prevent spawning is to move to farming triploid oysters (Nell, 2002). Triploids have an extra pair of chromosomes that render them sterile. They also have the added benefit of being saleable all year round compared to diploids that are in poor condition after spawning.

In early stages of naturalisation culling small populations, before reefs form, may be possible (Guy and Roberts, 2010). However, it is very difficult to access subtidal populations of any species. Once established, there are a number of possible mechanisms to prevent further spreading. One is to implement widespread eradication schemes. This will be very labour intensive and need to be conducted over successive years to make sure any remaining brood stock is removed. Alternatively, control may be possible through voluntary actions via marine practitioners, e.g., those who gather wild shellfish for commercial gain (Whelkers, Scallop divers) or through volunteer groups (e.g., the marine conservation society), or rarely, where threatened, by the action of other shellfish fisheries such as blue mussel growers. In other marine systems there have been bounties put on invasive species where official eradication attempts have failed. The European-wide organisation NORA Native Oyster Restoration Association are a strong pan-European body and are likely to target removal of *M. gigas* from any sites that are earmarked for Native Oyster restoration.

In Scotland, a synthesis of evidence is currently underway, but has not reported at the time of writing.

**What is the impact of current levels of adaptation at mitigating these risks?**

Currently the adaptation of *M. gigas* naturalisation in the UK is low as naturalisation is predominantly limited to south east England.

*Culling:* - Two culling trials have been conducted in the UK. In Strangford Loch, Northern Ireland, where abundances are very low (< 1 per $m^2$) and settlement thresholds are rarely exceeded, mechanical removal seems successful (Guy and Roberts, 2010). In southeast England, where extensive reefs are found, a pilot trial where 40,000 oysters were removed was conducted in 2015. However, resurveys of culled areas have not yet been conducted (McKnight and Chudleigh, 2015).

*Exploitation:* - A dredge fishery operates in the Blackwater Estuary, Essex for both *M. gigas* and *O. edulis.* Handpicking of seed in the estuary also prevents widespread reef formation.

*Table 48.* ***Adapting to temperature impacts on Pacific oyster, M. gigas***

| Nature of adaptation | Current status & plans | Benefits of adaptation since 2012 | Potential further action or investigation | Case for action in the next 5 years |
|---|---|---|---|---|
| Farm triploid stock of *M.gigas* to prevent damage to native species | Not widely practiced | N/A | **Delivering adaptation:**<br>Regulation: some regulatory action could be taken to protect species at risk from *M.gigas*<br>Advice: distribution of information on managing existing oyster populations and any new species<br>Incentives: incentives (grants or similar) could be provided to encourage farming of triploid stock of *M.gigas.*<br><br>**Building capacity:**<br>Increased awareness regarding identification may be required, as well as promotion of effective means of eradication.<br>Coordination will be required across neighbouring populations as well as on an international scale in order for actions to be effective; therefore capacity building may also be required elsewhere. | **Delivering adaptation:**<br>Implementing adaptation actions such as eradication or farming to reduce populations will reduce the impact that *M.gigas* has on native species of oyster. Unless action is taken on an international scale, the impacts may be limited.<br><br>**Building capacity:**<br>Raising awareness so that stakeholders are aware of the challenges and how to mitigate the risks of *M.gigas* within the next 5 years will assist in preventing established colonisation of *M.gigas*. |
| Eradication of *M.gigas* | Culling trials have been conducted in the UK: In Strangford Loch, Northern Ireland, where abundances are very low (< 1 per $m^2$) and settlement thresholds are rarely exceeded, mechanical removal seems successful (Guy and Roberts, 2010). In southeast England, where extensive reefs are found, a pilot trial where 40,000 oysters were removed was conducted in 2015. However, resurveys of culled areas have not yet been conducted (McKnight and Chudleigh, 2015). | N/A | | |
| **Is risk managed by autonomous or planned adaptation?** | | | | |

| |
|---|
| Planned adaptation would be required on an international scale due to the connected nature of marine environments and the high dispersal capacity of *M.gigas* larvae. The eradication of *M.gigas* would be very labour intensive and needs to be conducted over successive years to ensure the removal of any brood stock. Voluntary action may also help slow the spread of this species. |
| **Risks of lock-in**<br>Without adaptation actions there could be risk of *M. gigas* resulting in some sites losing conservation status or establishing into reefs which then cannot be removed. |
| **Risk(s) interacting**<br>Improvements in water quality<br>Potential negative impact on biodiversity |
| **Urgency scoring**<br>More urgent – research priority. There is a need to conduct more research to assess the magnitude of impact of this invasive species and therefore the need for additional action |

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Having pre-emptive rapid action plans in place for sites where *M. gigas* settlement will compromise the sites conservation status, may prevent settlement turning into reefs that cannot then be removed.

Pre-emptively moving to triploid farming in areas anticipated to exceed settlement thresholds in the future.

The adaptation response to the spread of *M. gigas* may be different in parts of the UK or over time as our understanding, especially of impacts, improves.

**In what scenarios are there limits to adaptation?**

*Large dispersal capacity*

The connected nature of marine environments and *M. gigas's* high dispersal capacity mean larvae can easily cross geographical and geopolitical boundaries. This means as climate change advances, there is a clear pathway for naturalisation into areas with no history of *M. gigas* cultivation. Moreover, any management interventions enacted on anything but an international scale may be severely compromised. For example, established populations in SW England are likely a result of immigration from French, rather than neighbouring English, populations (Lallias et al., 2013).

*Triploidy*

As triploid oysters are sterile, they have been proposed as a potential alternative to prevent spawning and settlement in *M. gigas.* However, there have been reports that triploid cells are not stable, with reversion back to diploids over time. On top of this, triploids can have mosaic cells (up to 20%) that also contain diploid cells (Allen et al., 1999). Therefore, switching to triploids may not prevent naturalisation.

Triploid seed costs more than diploids and many farmers may be reluctant or unable to pay extra. In addition, some food producers may wish to avoid using triploid stock as it may be termed "genetically modified" with associated negative connotations with consumers.

# 10 Freshwater – Case study: Algal blooms in lakes

This case study builds on the screening assessment (Section 5.3) by incorporating a wider set of climate projections into the analysis, which come from the climate model outputs for a RCP8.5 concentrations pathway (see Methods section). It shows the spatial variation in time course of threshold exceedance across the UK, and assesses the climate impacts in three clear time frames along the climate projections, for baseline, the 2050s and the 2080s. Climate data used are projections from CMIP5 and from PPE model ensembles (see Methods section 4.5). The threshold and main impacts are re-iterated below.

Figure 22 summarises the threshold and assessment chain. Lake temperatures are likely to warm in line with air temperature, with associated thermal stratification of lakes. Above a water temperature of 17 °C, and in combination with elevated nutrient levels, harmful algal blooms are more likely to form, leading to a decrease in water quality and adverse effects on the range of ecosystem services which are dependent on that water quality.

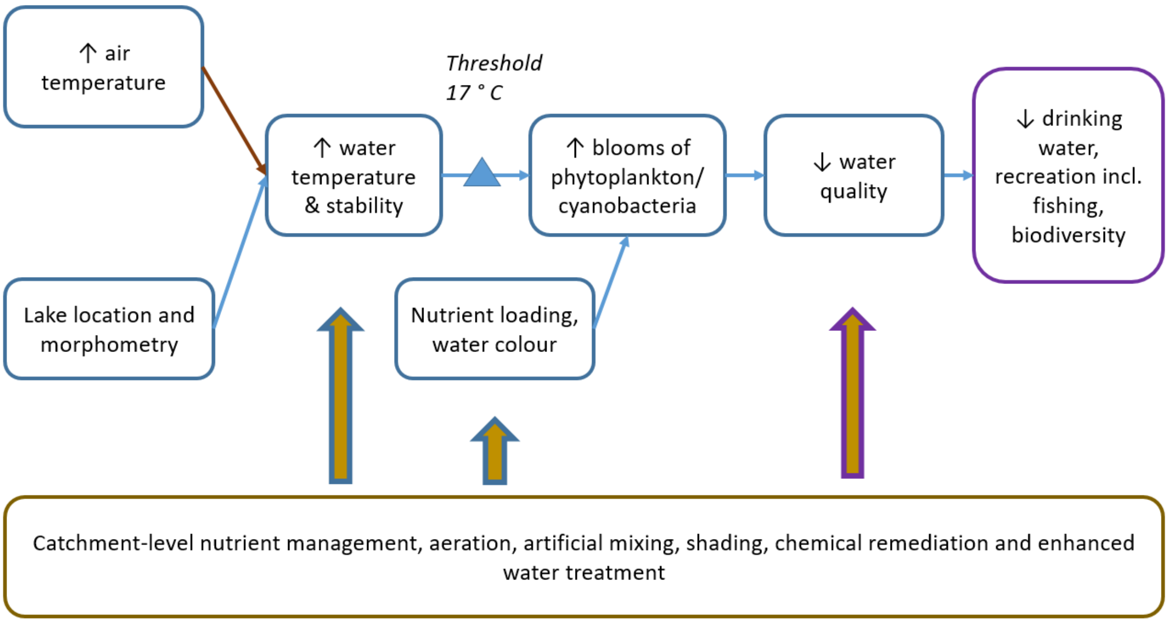



*Figure 22. **Impact chain for temperature effects on phytoplankton blooms in lakes**. Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures.*

**What climate hazard thresholds represent points beyond which the effective functioning of key systems within the natural environment may be compromised, and why?**

The climate threshold is a monthly mean lake water temperature of 17 °C, which equates to a monthly mean air temperature of 14.7 °C. Exceedance of this threshold is likely to lead to an increase in the incidence of algal blooms in lakes, although other factors such as nutrient inputs, lake size, depth, and turnover time also play a role. The evidence supporting the threshold and impacts is presented in the screening assessment, section 5.3.1.

Figure 23 plots the number of months each year that this threshold is exceeded, as an average across UK regions. Over the baseline period for this analysis of 1990-1999, the average number of months exceeding the threshold is broadly similar in the two model families and ranges from 1.58 – 1.75. The trajectory of change differs between the model predictions, and they start to diverge around 2020. The PPE model shows roughly linear increase in exceedance with time, while the CMIP5 models increase only slowly until around 2035, at which point exceedance starts to increase more rapidly. There is considerable spatial variability in when the models show a change in exceedance (Figure 24). In north Scotland, model averages suggest that exceedance of more than one month per year (below the UK average) does not occur until around 2050. By contrast, in London and south east England, the baseline period already shows exceedance for 3 months per year, and this increases steadily in both model families to a maximum of 5 months per year (CMIP5) or 6 months per year (PPE) in 2100.

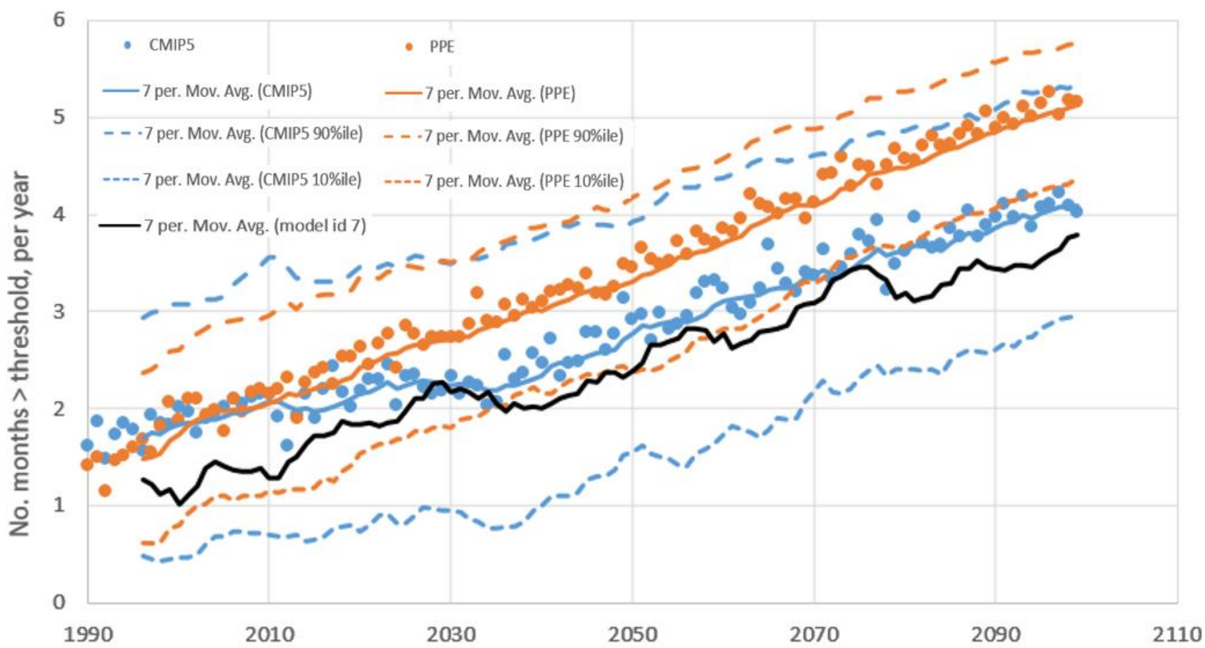



*Figure 23.* ***Time course of exceedance of water temperature threshold of 17 °C for algal blooms in lakes, under RCP8.5 pathway****. Data are UK average across regions, showing number of months exceeding threshold per year from 1990 – 2100, for two model families CMIP5 and PPE. Lines show median, 10 percentile (dotted line) and 90 percentile (dashed line) for each model family, comprising 13 ensemble members for CMIP5 (blue symbols) and 15 ensemble members for PPE (orange symbols). For comparison, black line shows PPE ensemble id 7, used in the national screening assessment.*

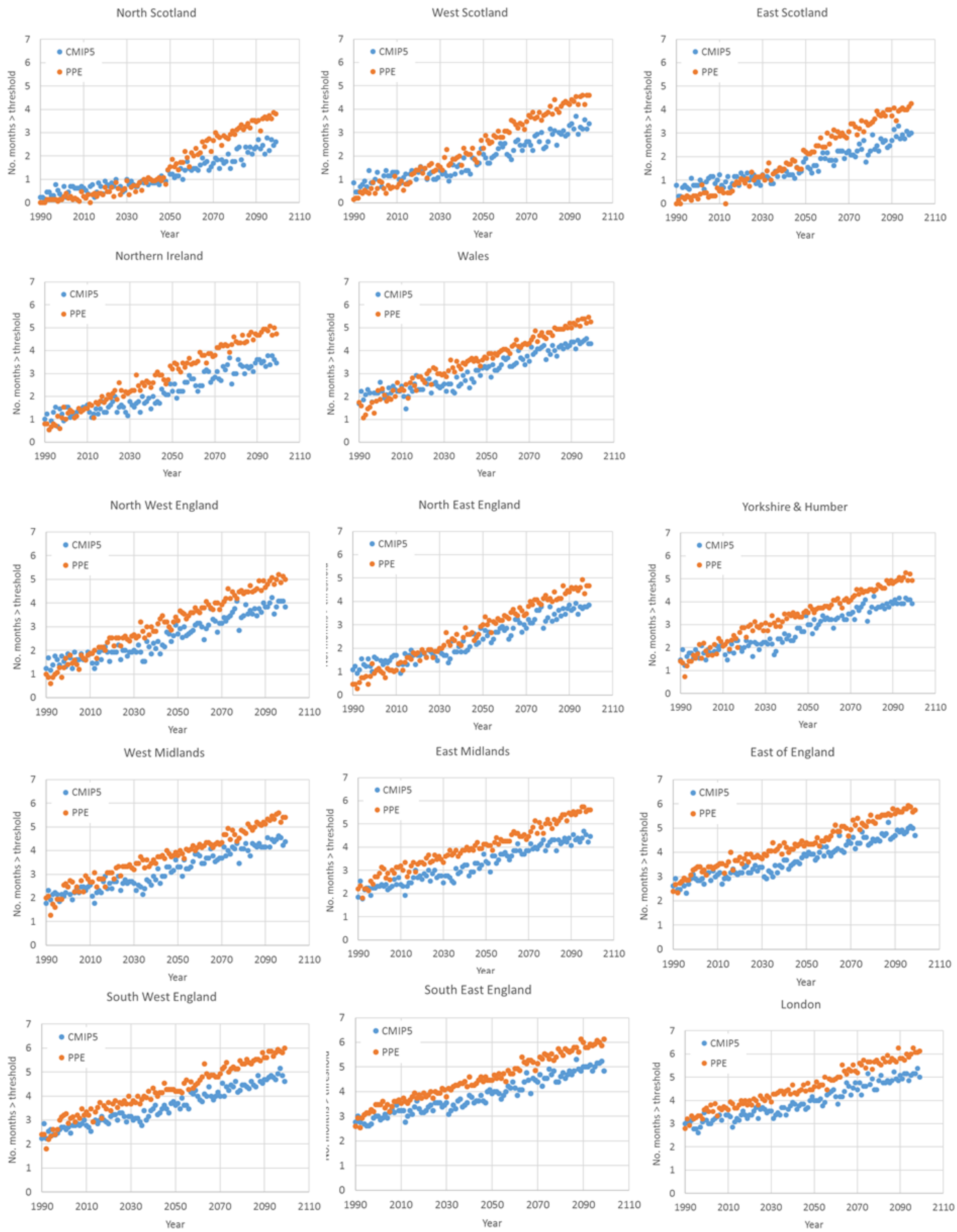



*Figure 24.* ***Time course, by UK climate region, of exceedance of lake water temperature threshold of 17 °C in lakes, under RCP8.5 pathway.*** *Data show number of months exceeding threshold per year from 1990 – 2100, for two model families CMIP5 and PPE. Each point represents the mean for a model family, comprising the following number of ensemble members: CMIP5 (13), PPE (15).*

Exceedance of the climate threshold by region for current day, 2050s and 2080s is shown in Table 49. Threshold exceedance is greater in the PPE models, but in both cases increases substantially from the baseline to the 2050s and further to the 2080s, approximately two-fold increase for CMIP5 by 2080s and three-fold increase for PPE by 2080s at UK level. In England, exceedance increases from around 2 months per year at baseline up to 3.3 and 4.1 months per year in the CMIP5 ensembles, for the 2050s and 2080s respectively. In the PPE ensembles, exceedance increases to 3.9 and 5.0 months in the 2050s and 2080s respectively. In Wales, the PPE ensembles increase from 1.5 months at baseline to 4.8 in the 2080s, while in Scotland, they increase from 0.2 months above the threshold at baseline to 3.4 in the 2080s. Northern Ireland shows a broadly similar pattern of exceedance to Wales.

*Table 49. **Number of months per year where monthly mean water temperature exceeds 17 °C threshold for algal blooms in lakes, by region of the UK, for current day, 2050s and 2080s under RCP8.5 pathway**. Data are averages across 13 ensemble members for CMIP5 and 15 ensemble members for PPE.*

| | CMIP5 | | | PPE | | |
|---|---|---|---|---|---|---|
| Region | Baseline (1990-99) | 2050s (2040-59) | 2080s (2070-89) | Baseline (1990-99) | 2050s (2040-59) | 2080s (2070-89) |
| North West England | 1.5 | 2.6 | 3.6 | 1.1 | 3.4 | 4.5 |
| North East England | 1.2 | 2.4 | 3.4 | 0.7 | 2.8 | 4.1 |
| Yorkshire and Humber | 1.7 | 2.9 | 3.7 | 1.5 | 3.6 | 4.5 |
| West Midlands | 2.1 | 3.3 | 4.1 | 2.0 | 3.9 | 4.8 |
| East Midlands | 2.2 | 3.3 | 4.1 | 2.3 | 4.1 | 5.0 |
| East of England | 2.7 | 3.8 | 4.6 | 2.8 | 4.3 | 5.3 |
| South West England | 2.5 | 3.6 | 4.4 | 2.5 | 4.3 | 5.3 |
| South East England | 2.8 | 3.9 | 4.7 | 3.0 | 4.5 | 5.6 |
| London | 3.0 | 4.0 | 4.8 | 3.2 | 4.6 | 5.7 |
| Wales | 2.1 | 3.1 | 4.0 | 1.6 | 3.7 | 4.8 |
| North Scotland | 0.4 | 1.1 | 1.9 | 0.1 | 1.4 | 3.0 |
| West Scotland | 0.8 | 1.9 | 2.8 | 0.4 | 2.4 | 3.9 |
| East Scotland | 0.7 | 1.5 | 2.4 | 0.2 | 2.0 | 3.5 |
| Northern Ireland | 1.1 | 2.2 | 3.2 | 0.9 | 3.1 | 4.4 |
| | | | | | | |
| Country averages | | | | | | |
| England | 2.2 | 3.3 | 4.1 | 2.1 | 3.9 | 5.0 |
| Wales | 2.1 | 3.1 | 4.0 | 1.6 | 3.7 | 4.8 |
| Scotland | 0.6 | 1.5 | 2.4 | 0.2 | 1.9 | 3.5 |
| Northern Ireland | 1.1 | 2.2 | 3.2 | 0.9 | 3.1 | 4.4 |
| **UK** | **1.8** | **2.8** | **3.7** | **1.6** | **3.4** | **4.6** |

**What are the resulting impacts on the goods and services provided to society from the natural environment? What would be the quantified impact?**

The impacts of algal blooms on lakes are broad-ranging. They encompass impacts on provisioning services such as water supply, regulating services linked to water and air quality, and cultural services such as recreation and amenity, as well as direct impacts on biodiversity. Economic assessment methods are outlined in the screening assessment (section 5.3)

The calculation of costs differs slightly from the approach in the screening assessment (section 5.3.4), in that future costs (Steps 3 and 4) are estimated by ratio for each region, and then summed to derive national totals. All steps for the case study analysis are described below for easy reference:

**Step 1:** Calculate annual baseline damages of algal blooms for 2001-2010 by adjusting for the change in consumer prices over time, since the study by Pretty et al (2003) was undertaken. These equate to an increase of 2.8% per year based on the level of consumer prices given by the Bank of England. This value was then scaled to a UK total from the England & Wales data reported in Pretty et al. (2003), as described above, using 2011 population data. Costs were then disaggregated to region based on a combined weighting of population and climate risk (number of months exceeding the threshold).

**Step 2**: Using estimates of monthly mean lake water temperatures exceeding 17°C under future temperature scenarios, calculate proportional increase in the average number of months where the water temperature threshold is exceeded, for each region.

**Step 3**: Using the assumption that the number of months of threshold exceedance drives the incidence of algal bloom outbreaks, we calculated the ratio of change in number of months exceeded for each region separately to the 2050s and the 2080s, relative to the baseline. We assume that baseline damage levels (from Pretty et al. 2003) reflect the impact of contributing factors such as excess nutrient levels, as well as existing levels of adaptation, and that these are held constant into the future.

**Step 4**: The future damage costs were calculated for each region separately, by multiplying baseline costs by the ratio of change in months exceeding the threshold, from Step 3. The national and UK totals were then summed from the regional cost estimates.

The estimated economic impact for each region of the UK is shown in Table 50. In both sets of model ensembles, impacts increase substantially in the 2050s and are even higher in the 2080s. In England the costs range from £291m for CMIP5 to £364m for PPE in the 2080s. The difference in the estimates reflects the hotter projections under PPE models. Economic impacts in Scotland, Wales and Northern Ireland are much lower and range from £7m to £25m in the 2080s depending on the model family. Most of these costs occur in England for three reasons. First, most waterbodies susceptible to HABs are in England implying higher baseline ecological risk. Second, the incidence of temperature threshold exceedance is greater in England increasing the risk of HABs in future. Third, economic costs are concentrated in more built-up regions in England, such as the South East and Midlands, due to impacts on a greater number of people who use the waterbodies.

*Table 50.* ***Economic impact of algal blooms in lakes due to exceedance of lake water temperature threshold (£ million), under RCP8.5 pathway, for baseline, 2050s and 2080s.*** *Economic values derived from Pretty et al. (2003) and calculated from data in Table 49 and Table 5. N.B. Baseline impacts are taken from Pretty et al. (2003), and scaled to the UK, so are the same for both models at UK level, although differ spatially when disaggregated down to region at baseline level.*

| | CMIP5 (£ million) | | | PPE (£ million) | | |
|---|---|---|---|---|---|---|
| **Region** | **Baseline (1990-99)** | **2050s (2040-59)** | **2080s (2070-89)** | **Baseline (1990-99)** | **2050s (2040-59)** | **2080s (2070-89)** |
| North West England | 13.7 | 24.2 | 32.7 | 10.0 | 32.1 | 42.6 |
| North East England | 4.1 | 8.2 | 11.3 | 2.3 | 10.0 | 14.4 |
| Yorkshire and Humber | 11.4 | 19.7 | 25.6 | 10.4 | 25.5 | 32.4 |
| West Midlands | 15.2 | 23.8 | 29.6 | 14.9 | 29.4 | 36.6 |
| East Midlands | 12.7 | 19.6 | 24.4 | 14.3 | 25.0 | 30.8 |
| East of England | 20.4 | 28.7 | 34.7 | 22.1 | 34.3 | 42.2 |
| South West England | 17.1 | 24.9 | 30.2 | 17.7 | 30.6 | 37.9 |
| South East England | 31.4 | 43.5 | 52.5 | 35.2 | 52.9 | 64.7 |
| London | 31.9 | 42.4 | 50.9 | 35.7 | 51.2 | 62.8 |
| Wales | 8.2 | 12.4 | 16.0 | 6.5 | 15.4 | 19.7 |
| North Scotland | 0.2 | 0.5 | 0.9 | 0.0 | 0.7 | 1.5 |
| West Scotland | 2.6 | 6.1 | 9.1 | 1.5 | 8.3 | 13.4 |
| East Scotland | 2.1 | 4.6 | 7.2 | 0.6 | 6.4 | 11.1 |
| Northern Ireland | 2.5 | 5.1 | 7.3 | 2.1 | 7.4 | 10.4 |
| | | | | | | |
| England total | 157.8 | 235.0 | 291.9 | 162.6 | 291.0 | 364.4 |
| Wales total | 8.2 | 12.4 | 16.0 | 6.5 | 15.4 | 19.7 |
| Scotland total | 4.9 | 11.3 | 17.1 | 2.1 | 15.3 | 25.9 |
| Northern Ireland total | 2.5 | 5.1 | 7.3 | 2.1 | 7.4 | 10.4 |
| **UK total** | **173.3** | **263.7** | **332.3** | **173.3** | **329.0** | **420.4** |

**Is there a risk of irreversible change in the ecosystems affected, or substantial time lags in recovery?**

Impacts depend to a large extent on contributing factors such as eutrophication (excess nitrogen and phosphorus inputs) and physical characteristics of the lakes. In large parts of the UK, these pre-conditions are already met, and algal blooms are being recorded in areas with relatively low climate risk such as East Scotland (0.68 months per year exceeding the threshold from CMIP5 models) at baseline. Once pre-conditions are met, lakes are likely to experience recurring algal blooms year on year. Long-term monitoring of the outcomes of restoration via catchment management at Loch Leven show that it can take decades for biogeochemical conditions to start to return to clean levels (Carvalho et al. 2011; Spears and May, 2014; Steinman and Spears, 2020). Furthermore, in shallow lakes, there is the possibility of shifts to a self-reinforcing stable, algae dominate state, which is then difficult to reverse (Scheffer et al 1993, Ibelings et al 2007). The long-term risks of warming for biodiversity are poorly understood, but some biodiversity recovery is possible where adaptation and mitigation, for example through nutrient reduction, can be achieved.

**What is the impact of current levels of adaptation at mitigating these risks?**

Recovery is dependent on a drop in lake water temperatures, which is difficult to achieve and needs to be addressed through climate change mitigation measures. Addressing the pre-conditions that make lakes more sensitive to the impacts of climate warming is therefore a key focus. This could involve options such as:

1) management of nutrient (nitrogen and phosphorus) delivery from the catchment by reducing sewage inputs from urban areas, and minimising losses of nutrients from agricultural land (e.g. as demonstrated in nitrate vulnerable zones),

2) use of in-lake/reservoir technologies to enhance mixing and reduce the light available for algal growth, or

3) geoengineering approaches to limit nutrient cycling of phosphorus between lake sediment and the overlying water column and to remove algal blooms from surface waters through flocculation.

Catchment-wide management of nitrogen and phosphorus diffuse sources and improved management of point sources, often domestic sewage, are the primary mechanisms for altering the pre-conditions for algal bloom formation. These are applied in nitrate vulnerable zones, but not widely elsewhere. Other aspects such as chemical remediation have been trialled in a limited number of severely affected water bodies, but not widely. Other management aspects such as riparian shading of lakes and input rivers have received relatively little focus so far, and are likely to be ineffective in large water bodies.

The falling number of surface water bodies in high or good ecological status, under the Water Framework Directive (see section 5.3.5), suggest that current measures to reduce catchment level nutrient inputs to waterbodies are minimal, and not sufficient to achieve the adaptation required to reduce this risk factor.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

The measures discussed in the previous section could be applied much more widely to reduce the likelihood of preconditions being favourable for algal bloom formation. Although not widely practiced currently, aeration by artificial mixing, e.g. through fans or pumps installed in the water body, and chemical remediation could also be used to reduce the impacts of algal blooms once they have formed.

**In what scenarios are there limits to adaptation?**

The adaptation methods apply in most cases to the pre-conditions necessary for algal bloom formation, therefore they are to a large extent independent of the climate risk. Lack of incentives or regulation may limit adoption of adaptation actions (e.g. nutrient management/buffer strips) by land owners, which would impact on the ability to prevent formation of algal blooms.

Once severe phytoplankton blooms have established, restoration activities may not be appropriate, depending on local conditions, and the likelihood/frequency of the algal bloom re-establishing. The larger the lake, and more severe the algal bloom, the more challenging adaptation can be. Ultimately, if the nutrient sources cannot be controlled, there is often little value in implementing other adaptation options, and efforts may best be focused on communicating and managing risks.

# 11 Farmland and grasslands – Case study: Temperature impacts on milk production

This case study builds on the screening assessment by incorporating a wider set of climate projections into the analysis, which come from the climate model outputs for a RCP8.5 concentrations pathway (see Methods section). It shows the spatial variation in time course of threshold exceedance across the UK, and assesses the climate impacts in three clear time frames along the climate projections, for baseline, the 2050s and the 2080s. Climate data used are projections from CMIP5 and from PPE model ensembles (see Methods section 4.5). The threshold and main impacts are re-iterated below.

Figure 25 summarises the threshold and assessment chain for the case study. Exceedance of the temperature humidity index (THI) threshold leads to declines in milk yield per cow, resulting in decreased milk production and costs to farmers.

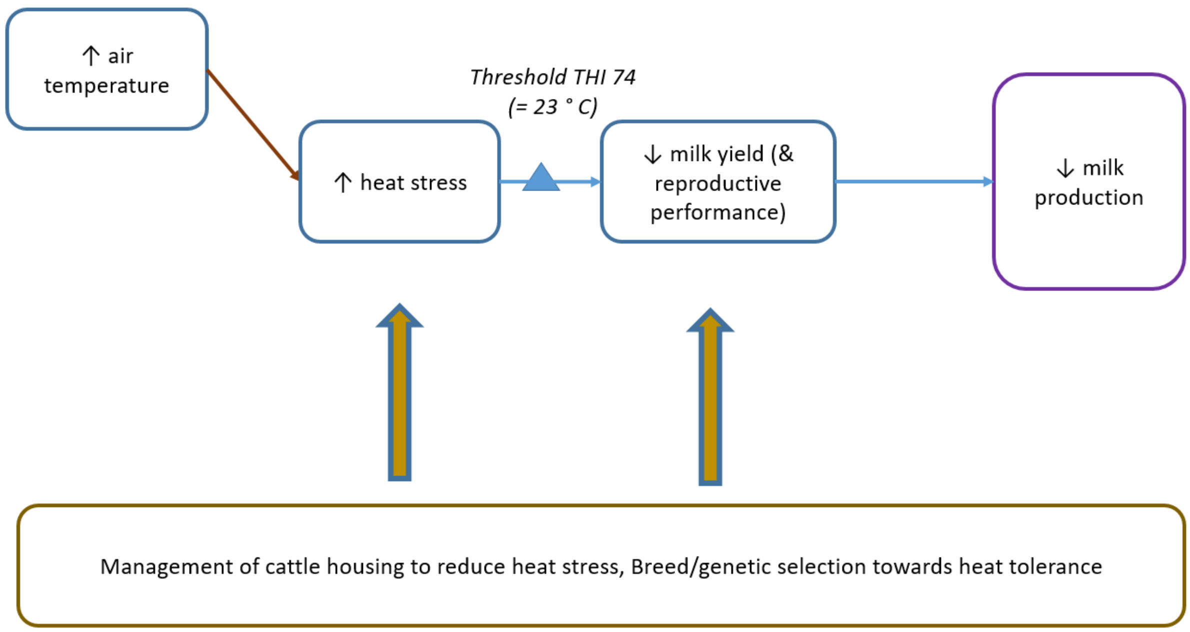



*Figure 25.* ***Impact chain for temperature effects on milk production****. Purple box shows endpoint social/economic impacts or impacts on biodiversity; Brown box shows potential adaptation measures.*

**What climate hazard thresholds represent points beyond which the effective functioning of key systems within the natural environment may be compromised, and why?**

The climate threshold is a temperature-humidity index (THI) of 74 (equates to a daily maximum air temperature of 23 °C, at 75% Relative Humidity (Dunn et al. 2014)). Exceedance of this threshold leads to a progressive decline in milk production, which is linear per unit increase in THI. The relationship between air temperature and THI is partly dependent on Relative Humidity, but not strongly so, and we assume a constant humidity value in this assessment (varying the humidity by as much as 20% only influences the THI by less than 0.7 of a unit). The evidence supporting the threshold and impacts is presented in the screening assessment, section 6.4.1.

Figure 26 plots the number of days per year across UK regions where THI exceeds 74 at 75% humidity. Over the baseline period for this analysis of 2000-2019, the average number of days exceeding the threshold is broadly similar in the CMIP5 and PPE ensembles and ranges from roughly 0 - 20. The trajectory of change differs between the model predictions, and they start to diverge around 2020, with faster increases in exceedance in the PPE model ensembles.

There is considerable spatial variability in when the models show a change in exceedance (see Figure 27). In north Scotland, the median of model outputs suggest that exceedance does not occur until around 2060. By contrast, in London and south east England, the baseline period already shows exceedance, although exceedance is slightly lower in the CMIP5 outputs than for PPE. Exceedance of the climate threshold by region for current day, 2050s and 2080s is shown in Table 51. Threshold exceedance is greater in the PPE models, but in both cases increases substantially from the baseline to the 2050s and even further to the 2080s, approximately three-fold increase by 2050s and six-fold increase by 2080s at UK level. Therefore there is also substantial spatial variation in the level of threshold exceedance, with threshold exceedance four to five times greater in England than in Scotland.

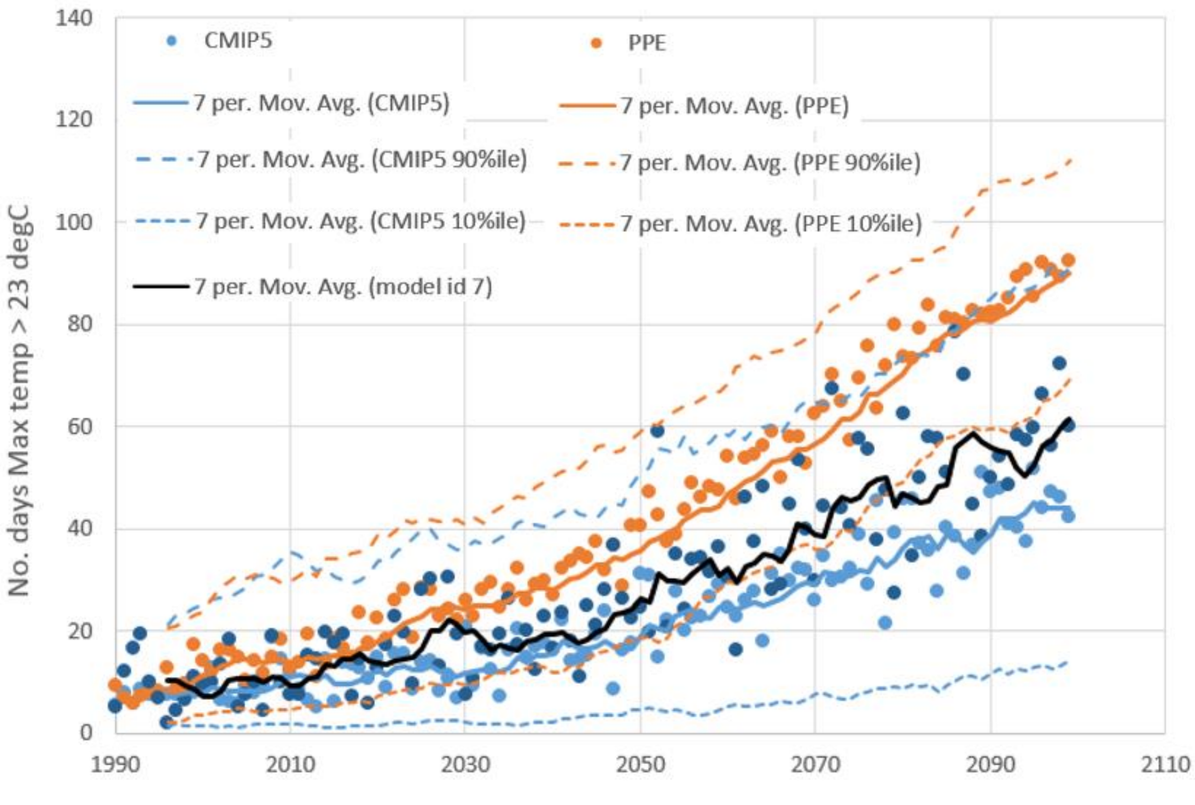



*Figure 26. **Time course of exceedance of maximum daily air temperature threshold of 23 °C for milk production, under RCP8.5 pathway.** Data are UK average across regions, showing number of days per year from 1990 – 2100, for two model families CMIP5 and PPE. Lines show 7-year moving average for median, 10 percentile (dotted line) and 90 percentile (dashed line) for each model family, comprising 13 ensemble members for CMIP5 (blue symbols) and 15 ensemble members for PPE (orange symbols).For reference, black line shows PPE model id 7, used in screening assessment.*

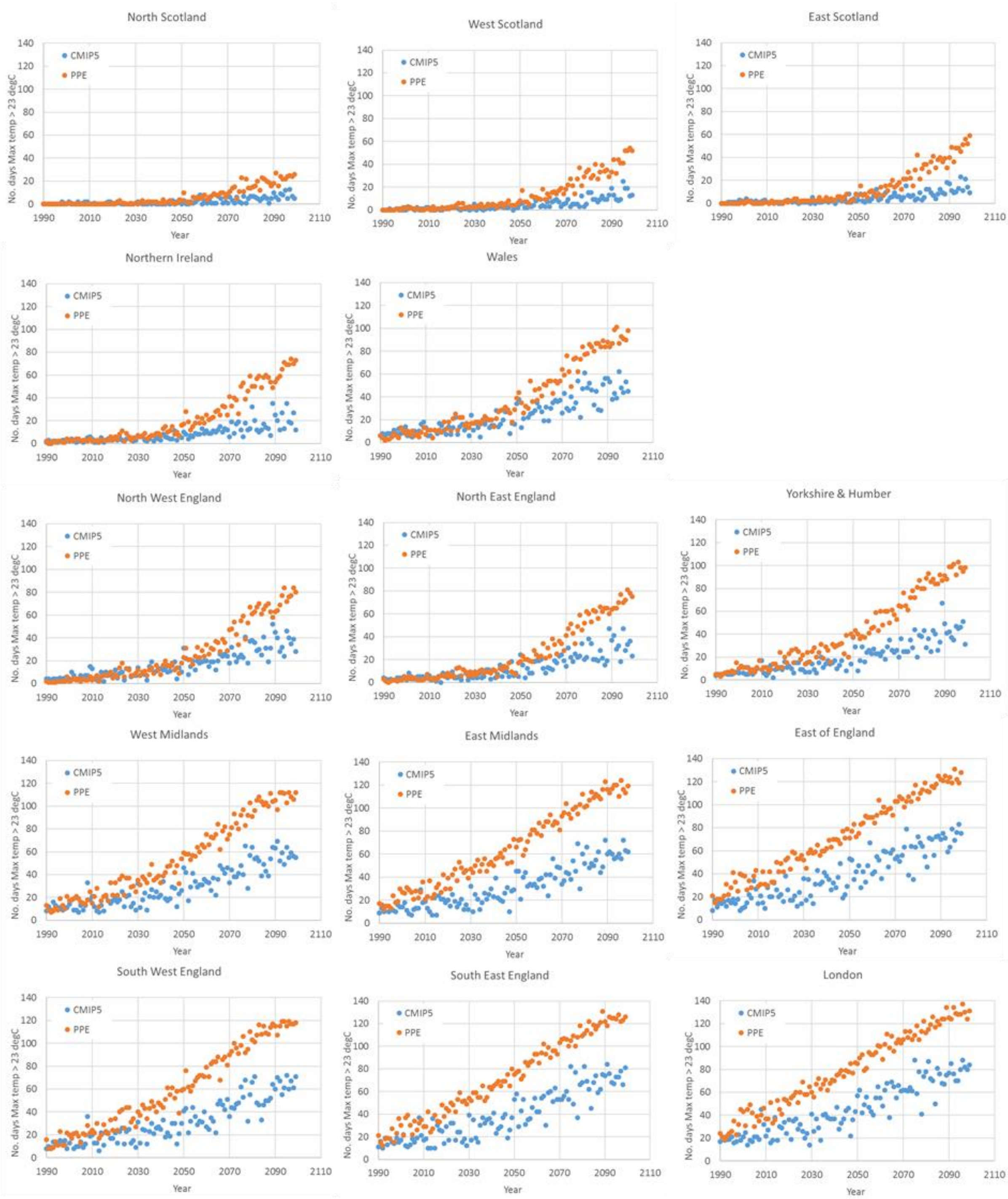



*Figure 27.* ***Time course, by UK climate region, of exceedance of daily maximum air temperature of 23 °C, number of days exceeding threshold per year from 1990 – 2100, under RCP8.5 pathway.*** *Data are from two model families CMIP5 and PPE. Each point represents the median for a model family, comprising 13 ensemble members for CMIP5 (blue symbols) and 15 ensemble members for PPE (orange symbols).*

*Table 51.* ***Number of days per year where THI exceeds 74 (maximum daily air temperature exceeds 23 °C) threshold under RCP8.5 pathway, by region of the UK, for baseline (current day), 2050s and 2080s****. Values are the average per year across the 20 year period of the median of 13 ensemble members for CMIP5 and 15 ensemble members for PPE.*

| | **CMIP5** | | | **PPE** | | |
|---|---|---|---|---|---|---|
| **Region** | Baseline (2000-19) | 2050s (2040-59) | 2080s (2070-89) | Baseline (2000-19) | 2050s (2040-59) | 2080s (2070-89) |
| North West England | 4.1 | 15.4 | 29.7 | 2.0 | 19.6 | 57.3 |
| North East England | 3.3 | 11.8 | 24.6 | 1.9 | 16.4 | 54.8 |
| Yorkshire and Humber | 5.4 | 19.4 | 33.8 | 6.7 | 35.3 | 79.2 |
| West Midlands | 11.1 | 28.3 | 47.3 | 12.0 | 51.6 | 95.2 |
| East Midlands | 12.0 | 30.3 | 50.2 | 17.9 | 65.6 | 104.6 |
| East of England | 14.3 | 38.1 | 60.2 | 23.3 | 75.5 | 110.0 |
| South West England | 11.9 | 29.5 | 50.7 | 13.3 | 59.9 | 103.5 |
| South East England | 15.0 | 37.5 | 62.5 | 20.4 | 74.8 | 111.7 |
| London | 18.9 | 44.5 | 68.7 | 27.1 | 84.2 | 116.4 |
| Wales | 8.2 | 23.1 | 40.2 | 5.4 | 31.6 | 75.6 |
| North Scotland | 0.2 | 1.4 | 4.2 | 0.1 | 3.3 | 15.6 |
| West Scotland | 0.4 | 3.4 | 8.2 | 0.3 | 7.3 | 29.0 |
| East Scotland | 0.9 | 3.7 | 8.2 | 0.2 | 6.7 | 30.8 |
| Northern Ireland | 2.1 | 6.9 | 15.2 | 1.5 | 15.1 | 48.5 |
| England (average of regions) | 10.7 | 28.3 | 47.5 | 13.8 | 53.6 | 92.5 |
| Wales | 8.2 | 23.1 | 40.2 | 5.4 | 31.6 | 75.6 |
| Scotland (average of regions) | 0.5 | 2.8 | 6.8 | 0.2 | 5.7 | 25.1 |
| Northern Ireland | 2.1 | 6.9 | 15.2 | 1.5 | 15.1 | 48.5 |
| **UK (average of regions)** | **7.7** | **20.9** | **36.0** | **9.4** | **39.0** | **73.7** |

When converted to the daily accumulated exceedance of THI units above the threshold, the trajectory over time shows a much steeper increase (Figure 28), with the greatest change occurring after the 2050s. There is also a greater divergence between the predictions from the two sets of model ensembles, with PPE ensembles leading to much higher cumulative THI units than the PPE ensembles.

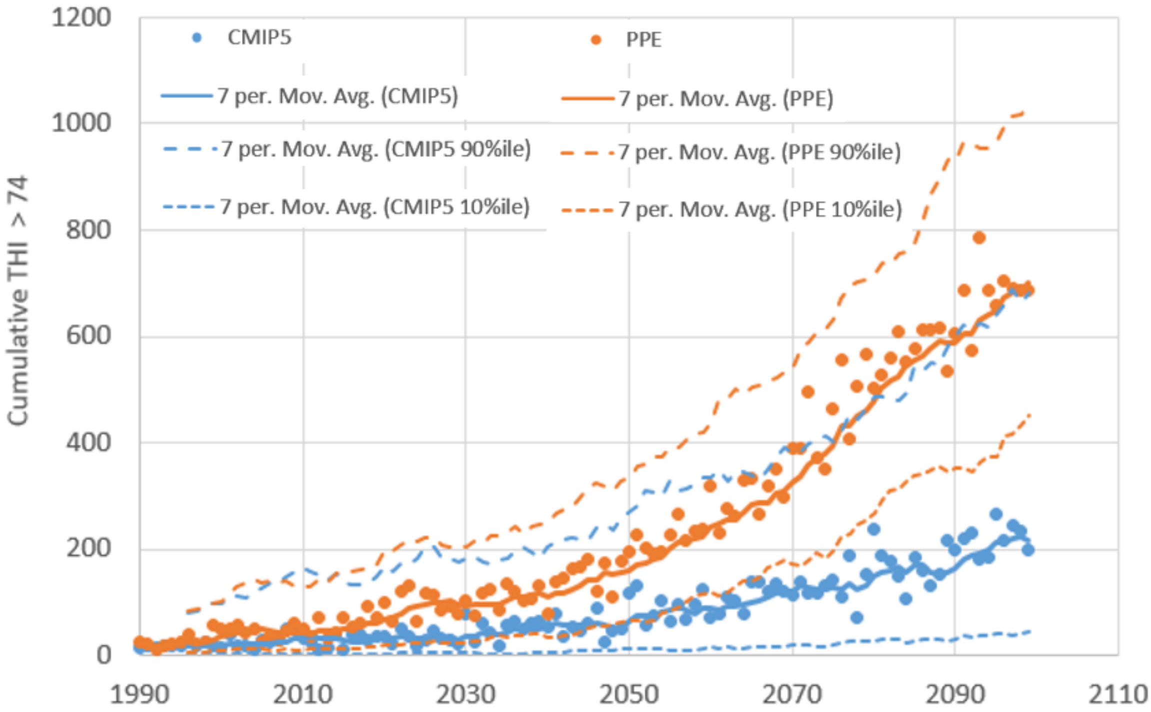



*Figure 28.* ***Time-course of cumulative exceedance of THI above threshold per year, from 1990 – 2100, under RCP8.5 pathway.*** *Data are UK average across regions, for two model families CMIP5 and PPE. Lines show 7-year moving average for median, 10 percentile (dotted line) and 90 percentile (dashed line) for each model family, comprising 13 ensemble members for CMIP5 (blue symbols) and 15 ensemble members for PPE (orange symbols).*

**What are the resulting impacts on the goods and services provided to society from the natural environment? What would be the quantified impact?**

Exceedance of the air temperature threshold has two main impacts on dairy cows. It leads to a decline in milk production Mukherjee *et al.,* 2012; Polsky and von Keyerslingk, 2017), and decreased conception rates (Wolfenson and Roth, 2019). For this assessment we focus on declines in milk production.

The method for calculating changes in milk yield differs in the case study from that in the screening assessment, since it takes into account the amount of exceedance above the THI threshold (the number of THI units above the threshold) on each day. Total milk production losses per region were calculated by multiplying cumulative THI exceedance above the threshold, by the milk loss per THI unit, and by the number of cattle in each region.

The calculated time course of milk production losses is shown in Figure 29. This shows a steep increase in total milk losses after the 2050s, with a much steeper rise projected when using the PPE model projections. The estimated economic impact for each region of the UK is shown in Table 52. At the UK level, impacts under baseline climate range from £3 – £4.5 million depending on the model projections chosen. Under the CMIP5 ensembles, costs increase to £8 million by 2050s and to £17 million in 2080s. The costs are much larger under the PPE projections reaching £18 million in 2050s and £57 million in 2080s.

In England, economic impacts range from £13 million for CMIP5 to £45 million for PPE in the 2080s. The large share of costs in England reflects that 60% of cows are currently reared there and threshold temperature exceedances tend to occur more frequently in England compared with other regions. Economic impacts in Scotland, Wales and Northern Ireland range from £0m to £7m in the 2080s depending on the model family.

The magnitude of these impacts compared to current UK value of milk production implies that by 2080 milk losses would total around 0.4% of total production value under CMIP5 and 1.3% under the PPE projections. The regions most impacted include south west England, north west England, the west Midlands, Wales and Northern Ireland (Table 52).

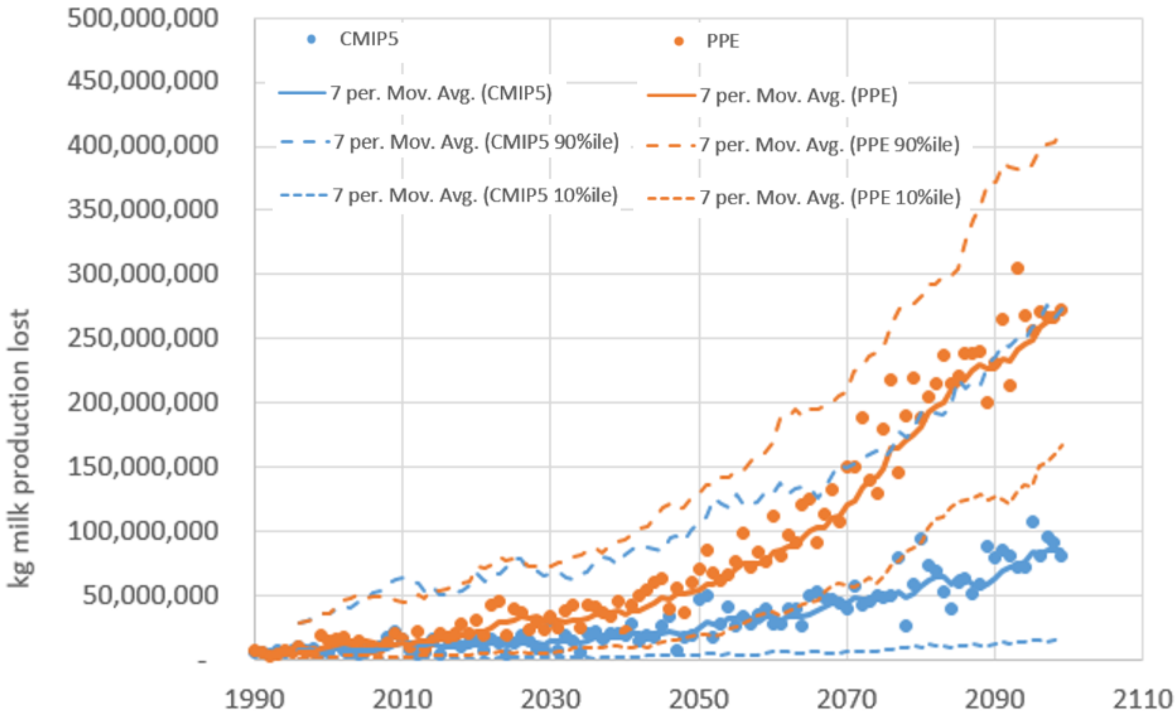



*Figure 29. **Time-course of loss of milk production (kg) for UK per year, from 1990 – 2100, under RCP8.5 pathway**. Data are for two model families CMIP5 and PPE. Lines show 7-period moving average for median, 10 percentile (dotted line) and 90 percentile (dashed line) for each model family, comprising 13 ensemble members for CMIP5 (blue symbols) and 15 ensemble members for PPE (orange symbols).*

*Table 52.* ***Economic impact of lost milk production due to exceedance of air temperature threshold (£ million), under RCP8.5 pathway, for baseline, 2050s and 2080s.***

| | **CMIP5** | | | **PPE** | | |
|---|---|---|---|---|---|---|
| **Region** | Baseline (2000-19) | 2050s (2040-59) | 2080s (2070-89) | Baseline (2000-19) | 2050s (2040-59) | 2080s (2070-89) |
| North West England | 0.3 | 0.8 | 1.9 | 0.2 | 1.1 | 5.0 |
| North East England | <0.1 | <0.1 | 0.1 | <0.1 | <0.1 | 0.2 |
| Yorkshire and Humber | 0.1 | 0.3 | 0.7 | 0.2 | 0.7 | 2.5 |
| West Midlands | 0.4 | 1.0 | 2.1 | 0.6 | 2.5 | 7.3 |
| East Midlands | 0.2 | 0.5 | 1.0 | 0.5 | 1.6 | 4.0 |
| East of England | 0.1 | 0.1 | 0.2 | 0.1 | 0.4 | 0.8 |
| South West England | 1.2 | 3.1 | 5.9 | 2.0 | 7.7 | 21.8 |
| South East England | 0.2 | 0.6 | 1.1 | 0.4 | 1.5 | 3.6 |
| London | - | - | - | - | - | - |
| Wales | 0.5 | 1.3 | 2.8 | 0.4 | 2.0 | 7.4 |
| North Scotland | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| West Scotland | <0.1 | 0.1 | 0.2 | <0.1 | 0.2 | 1.1 |
| East Scotland | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | 0.2 |
| Northern Ireland | 0.1 | 0.4 | 1.0 | 0.1 | 0.8 | 4.0 |
| England total | 2.5 | 6.5 | 13.0 | 4.1 | 15.4 | 45.2 |
| Wales total | 0.5 | 1.3 | 2.8 | 0.4 | 2.0 | 7.4 |
| Scotland total | <0.1 | 0.1 | 0.2 | <0.1 | 0.2 | 1.3 |
| Northern Ireland total | 0.1 | 0.4 | 1.0 | 0.1 | 0.8 | 4.0 |
| **UK total** | **3.1** | **8.1** | **17.0** | **4.6** | **18.4** | **57.9** |

**Is there a risk of irreversible change in the ecosystems affected, or substantial time lags in recovery?**

Impacts on milk production are highly dynamic and change with temperature on a timescale of days to weeks. Impacts on reproductive success, not quantified in this assessment, may have slightly longer term implications, but only on a yearly timescale. Therefore, in terms of biophysical responses of dairy cattle to temperature to elevated temperature there are no irreversible changes and no substantial time lags in recovery.

**What is the impact of current levels of adaptation at mitigating these risks?**

Current levels of adaptation are low as heat stress is not considered to be a major issue in the UK; therefore the impact of adaptation is low. Guidance is provided by organisations such as AHDB on how to reduce heat stress in livestock. With heat stress becoming more apparent in recent years, increasing adaptation may be seen in future years. In theory, basic adaptation actions such as providing access to shade and building ventilation should be reasonably effective at mitigating the risks of heat stress.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Installing shade for grazing cattle, installing fans and sprinklers in dairy herd housing, and research on how different breeds are affected by THI could all be undertaken in advance to reduce the risk of the THI threshold being crossed. The impact on milk production once the threshold has been crossed will be lessened where these actions have been taken up. These management options make it possible for milk production to continue, however, this could cause lock-in as cows may need to be permanently housed with a heavy reliance on internal systems to cool the indoor environment. The need for infrastructure can be avoided if there is a transition to different breeds, or using genetic selection for heat tolerance. The risk is greater, and occurs earlier, in the south and west of the UK than it does in Scotland. Therefore these areas should prioritise adaptation measures.

**In what scenarios are there limits to adaptation?**

Small scale farmers may not be economically equipped for adaptation where a capital-intensive housing approach is adopted. The option to relocate dairying further north is limited by the high infrastructure costs associated with this enterprise and the scale of investment for new sites. Processing capacity also reflects the current location of the sector in the south and west of England and places economic constraints on haulage of a bulk fresh product.

# 12 Peatlands – Case study: Temperature impacts on greenhouse gas emissions

This case study builds on the screening assessment by applying an improved rule base to apportion habitat change from one condition class to another, based on the climate pressure. It also incorporates a wider set of climate projections into the analysis, which come from the climate model outputs for a RCP8.5 concentrations pathway (see Methods section). It shows the spatial variation in time course of threshold exceedance across the UK, and assesses the climate impacts in three clear time frames along the climate projections, for baseline, the 2050s and the 2080s. Climate data used are projections from CMIP5 and from PPE model ensembles (see Methods section 4.5). The threshold and main impacts are re-iterated below.

Exceedance of the threshold mean temperature of the warmest month leads to declines in sphagnum cover and deterioration of the bog surface, which leads to increased peat oxidation and increased greenhouse gas emissions. The threshold and impacts are summarised in Figure 30.

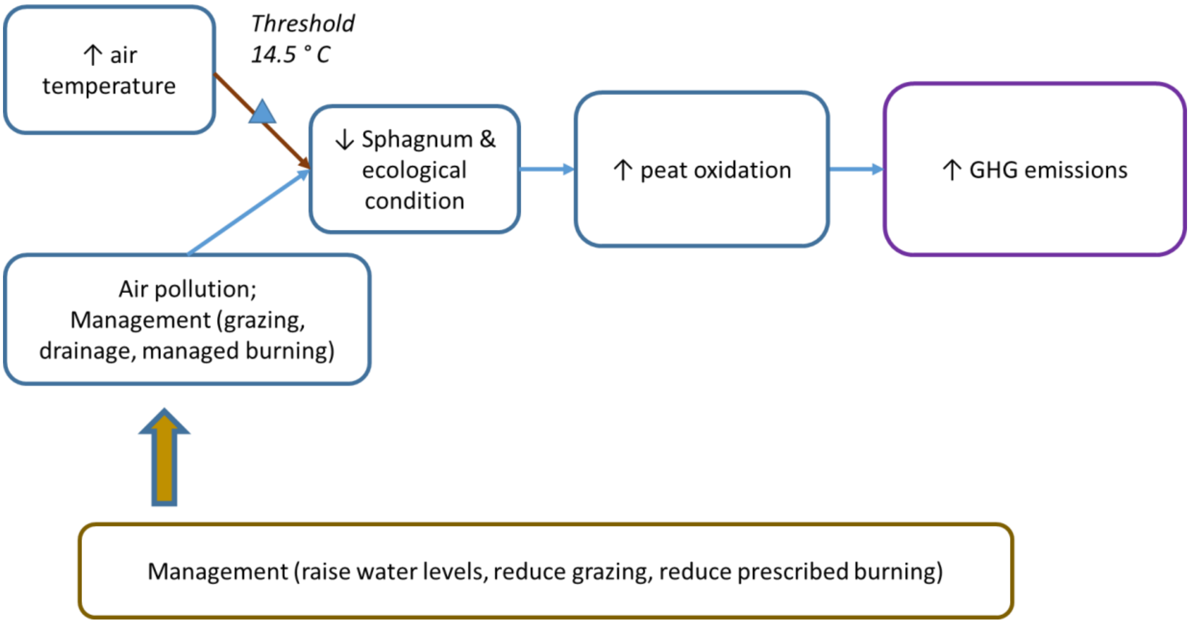



*Figure 30. **Impact chain for temperature effects on peatland GHG emissions**. Purple box shows endpoint social/economic impacts or impacts on biodiversity; Brown box shows potential adaptation measures. The threshold is based on long-term temperature of warmest month under the assumption that this encapsulates most associated drought effects. This is caveated with the knowledge that the climate envelope of peatlands is still poorly understood, and peatlands exist in either warmer, or drier, areas of the world than its UK distribution would suggest.*

**What climate hazard thresholds represent points beyond which the effective functioning of key systems within the natural environment may be compromised, and why?**

The climate threshold is a 30-year mean temperature of 14.5 °C for the warmest month (Gallego-Sala & Prentice, 2013). The evidence supporting the threshold and impacts is presented in the screening assessment, section 7.3.1.

Exceedance of this threshold has been shown to lead to a decline in the ecological integrity of peatlands, triggered by a loss of Sphagnum cover, and an increase in bare, eroding areas, oxidation of the exposed drying peat, and an increase in greenhouse gas emissions.

Figure 31 plots the 30 year rolling mean temperature of the warmest month, showing the median value from a suite of 28 climate ensemble members, and averaged across all UK regions. As a UK average across regions, the 14.5 °C threshold is exceeded already during the baseline period for this analysis (30-year mean, centred around 2004). In the CMIP5 model ensembles, the temperature remains reasonably low, but starts to increase by the 2030s, while in the PPE model ensembles, the temperature rises steadily from the baseline period, with the rate of rise steepening from the 2050s.

There is considerable spatial variability in the timing of when exceedance starts (see Figure 32, which only shows regions where peat currently occurs). In Scottish regions, the threshold is not exceeded until around the 2040s in the CMIP5 ensembles, but this happens much earlier in the PPE ensembles, in the mid 2020s. In most parts of northern England and in Northern Ireland the threshold is not exceeded at baseline, although rapidly becomes so. However, in Wales, Yorkshire & Humber and South West England, the threshold is exceeded even at baseline in all climate datasets.

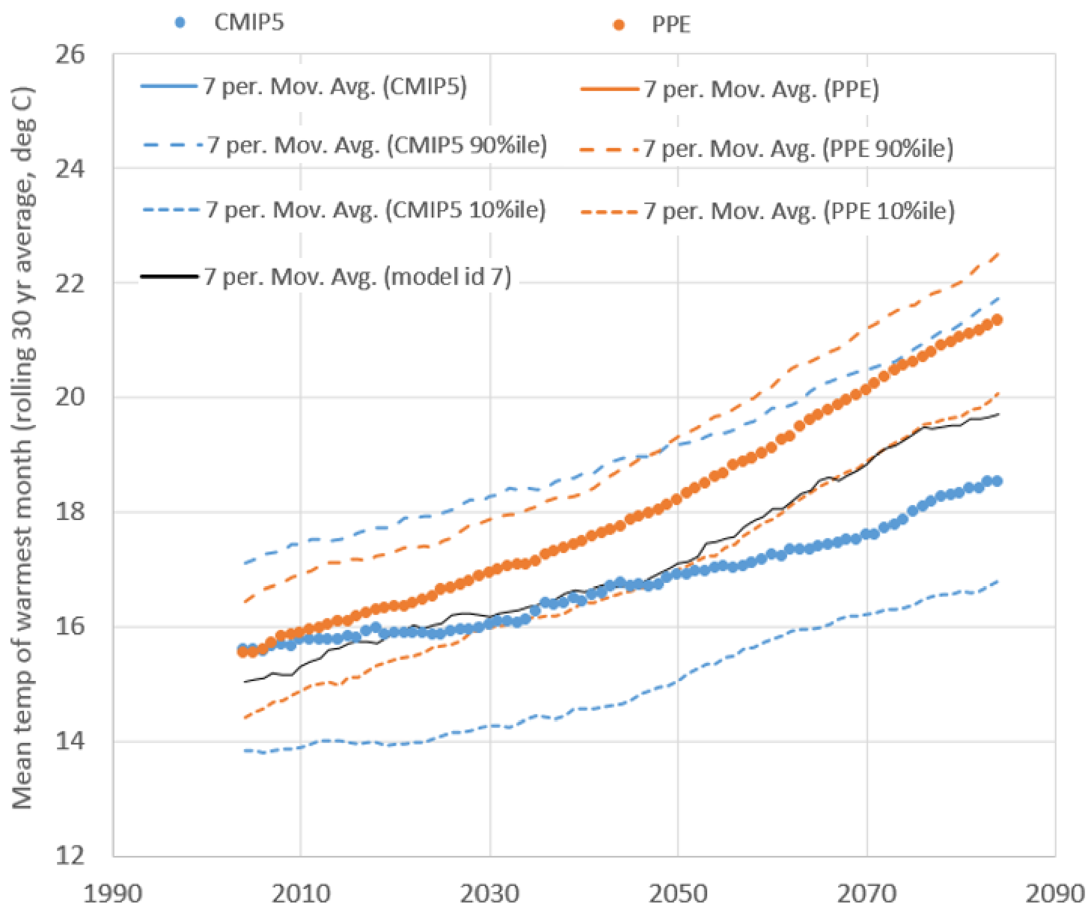



*Figure 31. **Time course of rolling 30-year mean temperature of the warmest month, under RCP8.5 pathway**. A 30-yr mean temperature of 14.5 °C is the threshold for declines in peatland integrity. Graph is constructed with data from 1990 – 2100, for two model families CMIP5 and PPE. Lines show median, 10 percentile (dotted line) and 90 percentile (dashed line) for each model family, comprising 13 ensemble members for CMIP5 (blue symbols) and 15 ensemble members for PPE (orange symbols). Black line shows trajectory of PPE model id 7 used in the screening assessment, for comparison.*

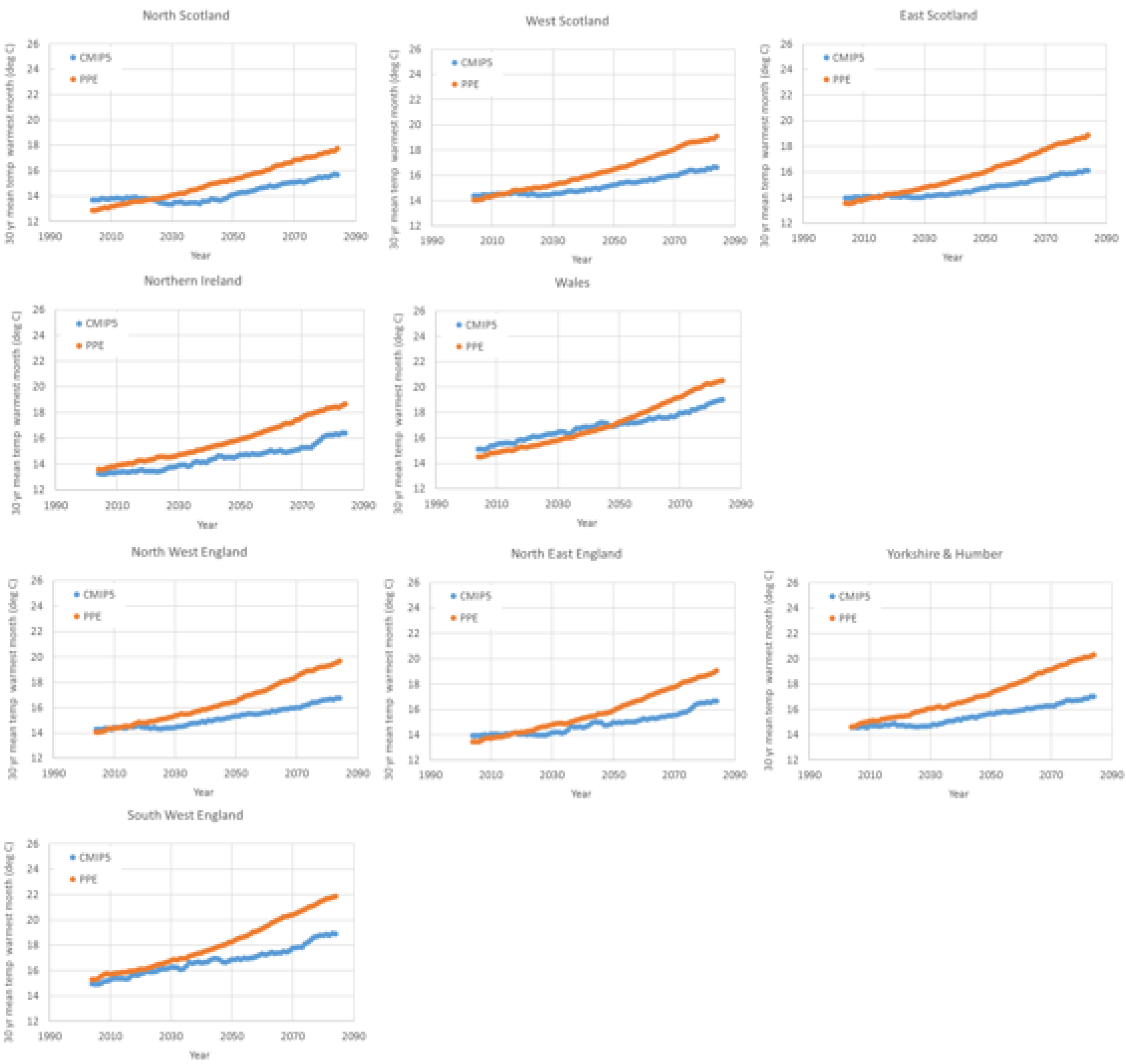



*Figure 32.* ***Time course, by region, of rolling 30-year mean temperature of the warmest month, under RCP8.5 pathway****. A 30-yr mean temperature of 14.5 °C is the threshold for declines in peatland integrity. Graph is constructed with data from 1990 – 2100, for two model families CMIP5 and PPE. Each point represents the 30 year average of the median for a model family, comprising 13 ensemble members for CMIP5 (blue symbols) and 15 ensemble members for PPE (orange symbols). Graphs for each region are shown in the same position, for comparison with other case studies.*

Exceedance of the climate threshold by region for baseline (30 year mean centred on 2004), 2050s (30 year mean centred on 2054) and 2080s (30 year mean centred on 2084) is shown in Table 53. As an average across UK regions containing blanket bog, the threshold exceedance is similar for the baseline period, at around 0.1 °C, but then is a factor of two higher in the PPE models compared with CMIP5, rising to 1 °C in the 2050s and 2.5 °C in the 2080s for CMIP5, but 2.4 °C and 5 °C respectively for PPE ensembles. This is driven by the faster rate of warming in PPE compared with CMIP5. In English regions with blanket bog the pattern is similar, although exceedance is slightly higher, rising to 2.8 °C for CMIP5 and 5.7 °C for PPE in the 2080s. In Wales, exceedance is somewhat higher, rising above 4 °C in both sets of model outputs in the 2080s, 4.5 °C for CMIP5 and 5.9 °C for PPE. Scotland and Northern Ireland do not show exceedance of the threshold at baseline, although both show exceedance in the 2050s, and both show exceedance greater than 4 °C in the PPE ensembles in the 2080s.

*Table 53.* ***Degrees above the threshold 30-year mean temperature of the warmest month (14.5 °C), by region of the UK, for baseline, 2050s and 2080s, under RCP8.5 pathway.*** *Values are the average per year across the 30 year period of the median of 13 ensemble members for CMIP5 and 15 ensemble members for PPE. Data only shown for regions containing blanket bog.*

| | **CMIP5** | | | **PPE** | | |
|---|---|---|---|---|---|---|
| **Region** | Baseline (1990-2019) | 2050s (2040-2069) | 2080s (2070-2099) | Baseline (1990-2019) | 2050s (2040-2069) | 2080s (2070-2099) |
| North West England | 0.0 | 1.0 | 2.3 | 0.0 | 2.5 | 5.2 |
| North East England | 0.0 | 0.5 | 2.2 | 0.0 | 1.9 | 4.6 |
| Yorkshire and Humber | 0.1 | 1.3 | 2.5 | 0.1 | 3.2 | 5.8 |
| West Midlands | - | - | - | - | - | - |
| East Midlands | - | - | - | - | - | - |
| East of England | - | - | - | - | - | - |
| South West England | 0.5 | 2.5 | 4.4 | 0.8 | 4.2 | 7.3 |
| South East England | - | - | - | - | - | - |
| London | - | - | - | - | - | - |
| Wales | 0.6 | 2.7 | 4.5 | 0.0 | 3.1 | 6.0 |
| North Scotland | 0.0 | 0.0 | 1.2 | 0.0 | 1.1 | 3.2 |
| West Scotland | 0.0 | 1.0 | 2.1 | 0.0 | 2.2 | 4.6 |
| East Scotland | 0.0 | 0.4 | 1.6 | 0.0 | 1.9 | 4.4 |
| Northern Ireland | 0.0 | 0.3 | 1.9 | 0.0 | 1.7 | 4.1 |
| England (average of regions with peat) | 0.14 | 1.34 | 2.84 | 0.24 | 2.92 | 5.72 |
| Wales | 0.62 | 2.71 | 4.52 | 0.02 | 3.10 | 5.99 |
| Scotland (average of regions with peat) | 0.00 | 0.47 | 1.64 | 0.00 | 1.75 | 4.07 |
| Northern Ireland | 0.00 | 0.29 | 1.91 | 0.00 | 1.68 | 4.14 |
| **UK (average of regions with peat)** | **0.13** | **1.08** | **2.52** | **0.11** | **2.41** | **5.03** |

These temperature changes result in a shift in the condition status of existing peatlands, following the rule base defined in Table 54. Note that condition at baseline reflects the current day situation, which includes the influence of current and historical land use decisions, management and restoration, as well as climate influences. Exceedance by > 4 °C is expected to result in complete shift from all condition categories to a highly modified state, based on observations from Bragazza (2008). Extrapolating from Bragazza (2008), exceedance of > 2 °C is expected to result in a complete shift of each condition category to the next category of poorer condition. Exceedance of less than 2 °C is expected to result in a partial shift of modified peatlands to a highly modified state, and a partial shift to the next condition category for near-natural and rewetted peatlands.

*Table 54.* ***Rule base for change in area of peatland condition categories under different levels of threshold exceedance***

| | Condition category | | |
|---|---|---|---|
| **Level of exceedance above long-term temperature threshold (°C)** | **Natural** | **Rewetted** | **Modified** |
| No exceedance | No change | No change | No change |
| 0 - 2 °C | 50% → Modified | 50% → Modified | 50% → Highly modified |
| 2 - 4 °C | 100% → Modified | 100% → Modified | 100% → Highly modified |
| > 4 °C | 100% → Highly modified | 100% → Highly modified | 100% → Highly modified |

Change in the extent of peatland within each condition category for the two sets of climate model ensembles are shown in Table 55 and Table 56, and summarised visually in Figure 33. At UK level, the area of highly modified peatland increases from around one fifth of the total at baseline to half of the total in the 2080s for the CMIP5 ensembles, and all peatland becomes highly modified in the 2080s for the PPE ensembles. This pattern remains broadly the same for each UK country, except in Wales, where the entire peatland area becomes highly modified in both CMIP5 and PPE ensembles by the 2080s, because the threshold exceedance rises above 4 °C in both cases (see Table 49).

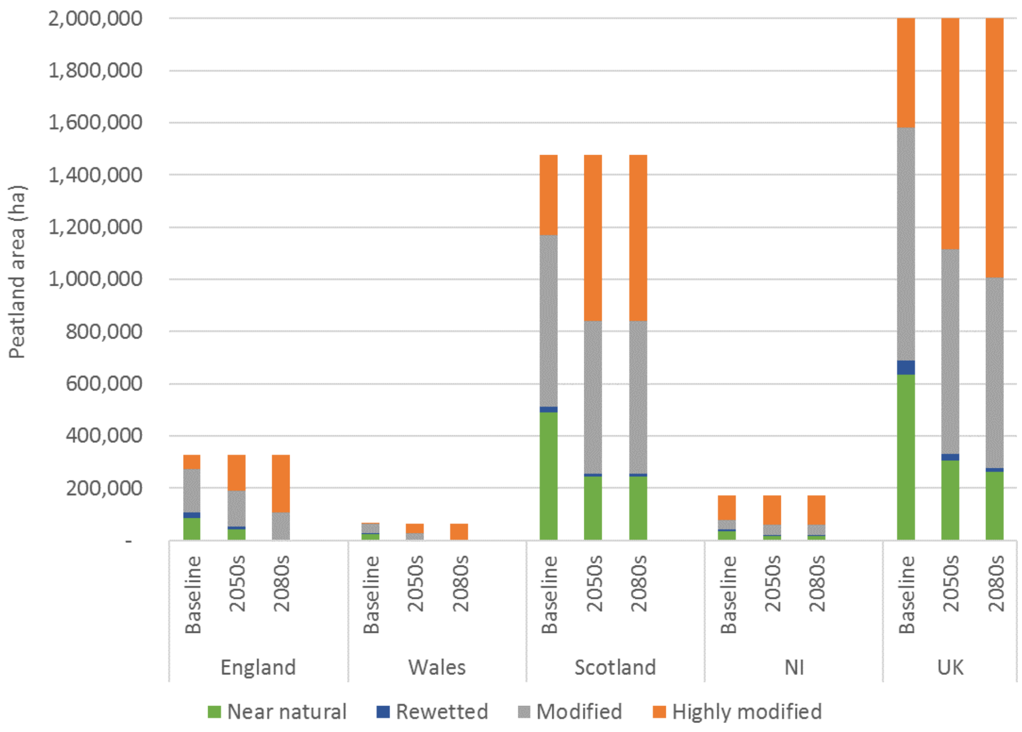
*Table 55.* ***Area of peatlands by UK country and by condition category, under RCP8.5 pathway, for baseline, 2050s and 2080s, <u>for median of CMIP5 ensembles.</u>*** *For description of categories, see Table 30.*

| | | Near natural | Rewetted | Modified | Highly modified | Total Peatland |
|---|---|---|---|---|---|---|
| **Baseline** | England | 84,000 | 24,000 | 164,000 | 53,000 | 326,000 |
| | Wales | 24,000 | 4,000 | 35,000 | 200 | 63,000 |
| | Scotland | 490,000 | 20,000 | 658,000 | 307,000 | 1,476,000 |
| | NI | 35,000 | 5,000 | 37,000 | 93,000 | 170,000 |
| | **UK** | **633,000** | **54,000** | **894,000** | **454,000** | **2,035,000** |
| | | | | | | |
| **2050s** | England | 42,000 | 12,000 | 136,000 | 135,000 | 326,000 |
| | Wales | - | - | 28,000 | 35,000 | 63,000 |
| | Scotland | 245,000 | 10,000 | 584,000 | 636,000 | 1,476,000 |
| | NI | 18,000 | 3,000 | 39,000 | 111,000 | 170,000 |
| | **UK** | **305,000** | **25,000** | **787,000** | **918,000** | **2,035,000** |
| | | | | | | |
| **2080s** | England | - | - | 108,000 | 217,000 | 326,000 |
| | Wales | - | - | - | 63,000 | 63,000 |
| | Scotland | 245,000 | 10,000 | 584,000 | 636,000 | 1,476,000 |
| | NI | 18,000 | 3,000 | 39,000 | 111,000 | 170,000 |
| | **UK** | **263,000** | **13,000** | **731,000** | **1,028,000** | **2,035,000** |

*Table 56.* ***Area of peatlands by UK country and by condition category, under RCP8.5 pathway, for baseline, 2050s and 2080s, <u>for median of PPE ensembles</u>***. *For description of categories, see Table 30.*

| | | Near natural | Rewetted | Modified | Highly modified | Total Peatland |
|---|---|---|---|---|---|---|
| **Baseline** | England | 84,000 | 24,000 | 164,000 | 53,000 | 326,000 |
| | Wales | 24,000 | 4,000 | 35,000 | 200 | 63,000 |
| | Scotland | 490,000 | 20,000 | 658,000 | 307,000 | 1,476,000 |
| | NI | 35,000 | 5,000 | 37,000 | 93,000 | 170,000 |
| | **UK** | **633,000** | **54,000** | **894,000** | **454,000** | **2,035,000** |
| | | | | | | |
| **2050s** | England | - | - | 108,000 | 217,000 | 326,000 |
| | Wales | - | - | 28,000 | 35,000 | 63,000 |
| | Scotland | 245,000 | 10,000 | 584,000 | 636,000 | 1,476,000 |
| | NI | 18,000 | 3,000 | 39,000 | 111,000 | 170,000 |
| | **UK** | **263,000** | **13,000** | **759,000** | **1,000,000** | **2,035,000** |
| | | | | | | |
| **2080s** | England | - | - | - | 326,000 | 326,000 |
| | Wales | - | - | - | 63,000 | 63,000 |
| | Scotland | - | - | - | 1,476,000 | 1,476,000 |
| | NI | - | - | - | 170,000 | 170,000 |
| | **UK** | **0** | **0** | **0** | **2,035,000** | **2,035,000** |

a) CMIP5 ensembles




b) PPE ensembles

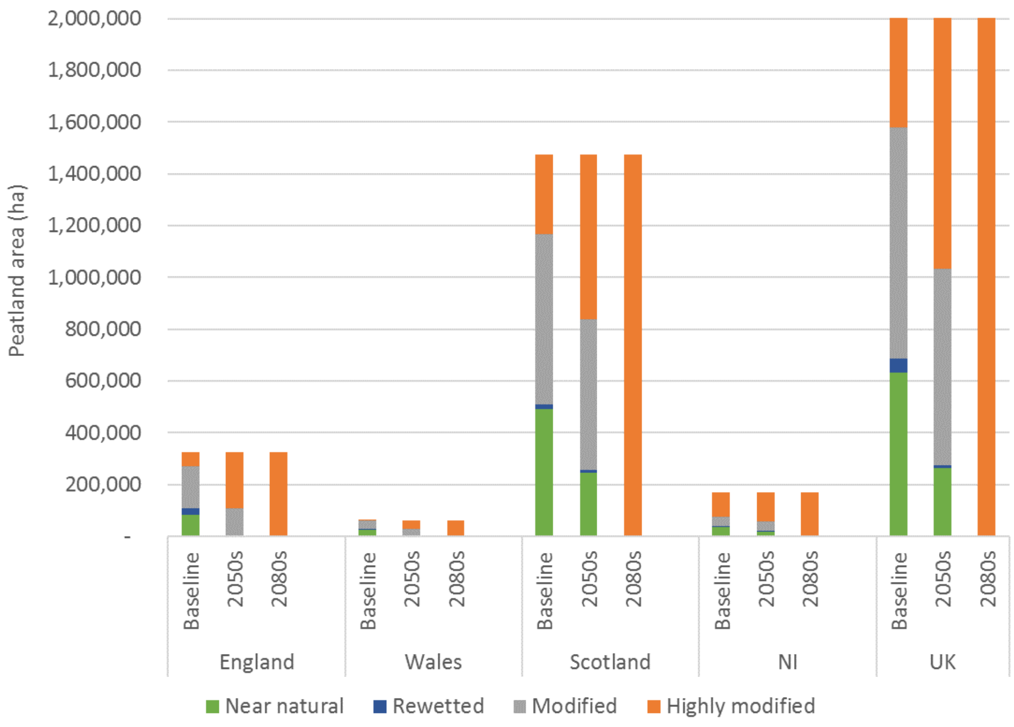



*Figure 33. **Area of peatlands by UK country and by condition category, under RCP8.5 pathway, for baseline, 2050s and 2080s**, for median of a) thirteen CMIP5 ensembles and b) fifteen PPE ensembles.*

**What are the resulting impacts on the goods and services provided to society from the natural environment? What would be the quantified impact?**

Exceedance of this threshold leads to degradation of peatlands with a consequent loss or decline of many of the ecosystem services that peatlands provide, including a loss of carbon sequestration and resulting changes in the greenhouse gas balance. The assessment focuses on valuing changes in greenhouse gas emissions, since robust methods for quantifying the economic value of other ecosystem services linked to changes in peatland condition, such as biodiversity, water quality and storage, currently do not exist (Martin-Ortega et al. 2014; Glenk and Martin-Ortega, 2018).

Emissions are calculated from the $CO_2$ equivalent emissions for each peatland category (adapted from Evans et al. 2017), see Table 57. The emission factors used in this assessment do not incorporate the effects of drainage in some areas of modified bog, which will lead to a slight under-estimate of the likely emissions. The total peatland area is assumed to remain unchanged, even under the most extreme scenario where all peatland shifts to a highly modified category. The use of emission factors also assumes that carbon loss from degraded peatlands will be gradual and sustained, thus giving lower estimates of carbon loss during the timescale of the scenario assessments; this is more conservative – but arguably more realistic – than predictions that the entire stock of carbon could be lost from peatlands that are no longer within their climate envelope (Ferreto et al., 2019). Socio-economic factors could also produce both positive and negative feedbacks on climate change impacts. For example if grasslands expand into blanket bog areas, or demand for UK food production increase, this could lead to increased grazing pressures and accelerated peat destabilisation. Conversely, widespread erosion and vegetation loss could result in the removal of grazing, allowing bogs to stabilise and recover. Finally, it is important to note that most of the UK's peatlands have withstood over 5000 years of climatic fluctuation, which suggests that they have a high level of intrinsic resilience, therefore it is possible that their capacity to withstand climate change (at least when in good condition) may be under-estimated by climate envelope models and thresholds. Therefore this assessment must be considered indicative of potential risks, with a high level of uncertainty, rather than as a projection of future change.

*Table 57.* ***Emission factors for peatland condition categories (adapted from Evans et al. 2017).***

| | Near natural bog | Rewetted bog | Modified (Grass/Heather dominated) | Highly modified |
|---|---|---|---|---|
| t CO2e /ha/yr | 0.01 | 0.81 | 2.08 | 3.55 |

The economic cost of emissions is calculated using the UK non-traded price of carbon[22], which reflects the cost of achieving the UK's carbon budget target, but not future changes in climate. Since future carbon price changes over time, we take the 30-year average of the non-traded carbon price for the future 2050 and 2080 time periods, and for baseline period we use the 2010 non-traded carbon price. The non-traded carbon prices used are shown in Table 58 below. The cost of emissions is calculated by multiplying the $CO_2$ equivalent emissions by the carbon price for that time period.

This assessment reports annual greenhouse gas emissions for all UK periods for two time periods, the 2050s and 2080s, assuming that ecological responses are in equilibrium with climate for each period.

*Table 58*. ***Cost per tonne $CO_2$ equivalent for carbon emissions***

| Year | Cost per tonne CO2e (£) |
|---|---:|
| 2010 | 60 |
| 2040 - 2069 | 261 |
| 2070 - 2099 | 342 |

GHG emissions are summarised in Table 59, and visualised in Figure 34. Emissions from near-natural peatlands and rewetted peatlands are negligible. This is because the emission factor for near-natural peatlands is virtually zero, and rewetted peatlands have a relatively low emission factor and they have a small area in the UK. Therefore the majority of emissions come from modified and highly modified peatland categories. Even at baseline, emissions from these categories come to around 3.5 million $tCO_2e$ at UK scale. This rises to around 5 million $tCO_2e$ in the 2050s and up to 5.1 million $tCO_2e$ in the 2080s for the CMIP5 ensembles, and 7.2 million $tCO_2e$ for the PPE ensembles. Scotland makes up the majority of these emissions (~65%), with emissions from English peatlands coming next (~20%).

[22] Valuation of Energy Use and Greenhouse Gas. Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government. Department for Business, Energy and Industrial Strategy. April 2019.

*Table 59.* ***GHG emissions (tCO2e) from peatlands by UK country and by condition category, under RCP8.5 pathway for baseline, 2050s and 2080s****, for median of a) thirteen CMIP5 ensembles and b) fifteen PPE ensembles.*

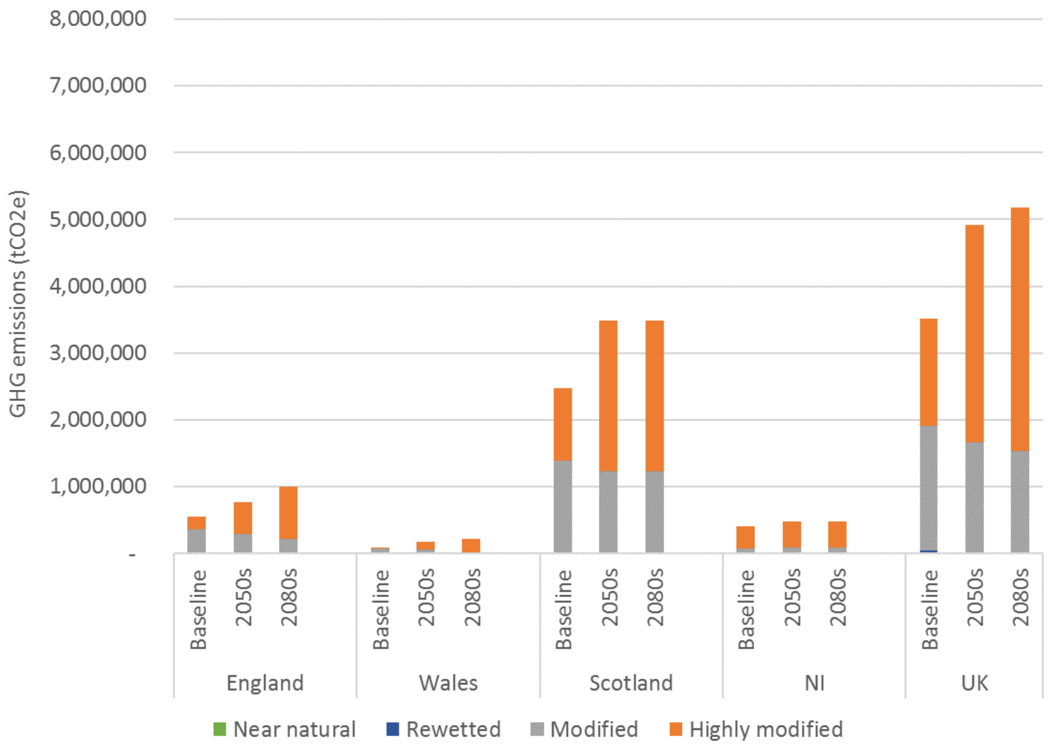
a) CMIP5 ensembles

| | | Near-natural | Rewetted | Modified | Highly modified | Total emissions |
|---|---|---|---|---|---|---|
| England | Baseline | 800 | 19,800 | 340,700 | 189,800 | 551,100 |
| | 2050s | 400 | 9,900 | 283,100 | 480,500 | 773,900 |
| | 2080s | - | - | 225,400 | 771,300 | 996,700 |
| Wales | Baseline | 200 | 3,300 | 73,300 | 700 | 77,500 |
| | 2050s | - | - | 57,300 | 125,900 | 183,200 |
| | 2080s | - | - | - | 223,700 | 223,700 |
| Scotland | Baseline | 4,900 | 16,500 | 1,368,400 | 1,090,400 | 2,480,300 |
| | 2050s | 2,500 | 8,300 | 1,215,600 | 2,258,200 | 3,484,500 |
| | 2080s | 2,500 | 8,300 | 1,215,600 | 2,258,200 | 3,484,500 |
| NI | Baseline | 400 | 4,300 | 76,200 | 330,700 | 411,500 |
| | 2050s | 200 | 2,200 | 80,200 | 395,700 | 478,200 |
| | 2080s | 200 | 2,200 | 80,200 | 395,700 | 478,200 |
| **UK** | **Baseline** | **6,300** | **43,900** | **1,858,600** | **1,611,600** | **3,520,500** |
| | **2050s** | **3,000** | **20,300** | **1,636,100** | **3,260,300** | **4,919,700** |
| | **2080s** | **2,600** | **10,400** | **1,521,100** | **3,648,800** | **5,183,000** |

b) PPE ensembles

| | | Near natural | Rewetted | Modified | Highly modified | Total emissions |
|---|---|---|---|---|---|---|
| England | Baseline | 800 | 19,800 | 340,700 | 189,800 | 551,100 |
| | 2050s | - | - | 225,400 | 771,300 | 996,700 |
| | 2080s | - | - | - | 1,156,000 | 1,156,000 |
| Wales | Baseline | 200 | 3,300 | 73,300 | 700 | 77,500 |
| | 2050s | - | - | 57,300 | 125,900 | 183,200 |
| | 2080s | - | - | - | 223,700 | 223,700 |
| Scotland | Baseline | 4,900 | 16,500 | 1,368,400 | 1,090,400 | 2,480,300 |
| | 2050s | 2,500 | 8,300 | 1,215,600 | 2,258,200 | 3,484,500 |
| | 2080s | - | - | - | 5,239,700 | 5,239,700 |
| NI | Baseline | 400 | 4,300 | 76,200 | 330,700 | 411,500 |
| | 2050s | 200 | 2,200 | 80,200 | 395,700 | 478,200 |
| | 2080s | - | - | - | 604,300 | 604,300 |
| **UK** | **Baseline** | **6,300** | **43,900** | **1,858,600** | **1,611,600** | **3,520,500** |
| | **2050s** | **2,600** | **10,400** | **1,578,400** | **3,551,000** | **5,142,500** |
| | **2080s** | **-** | **-** | **-** | **7,223,600** | **7,223,600** |

a) CMIP5 ensembles




b) PPE ensembles

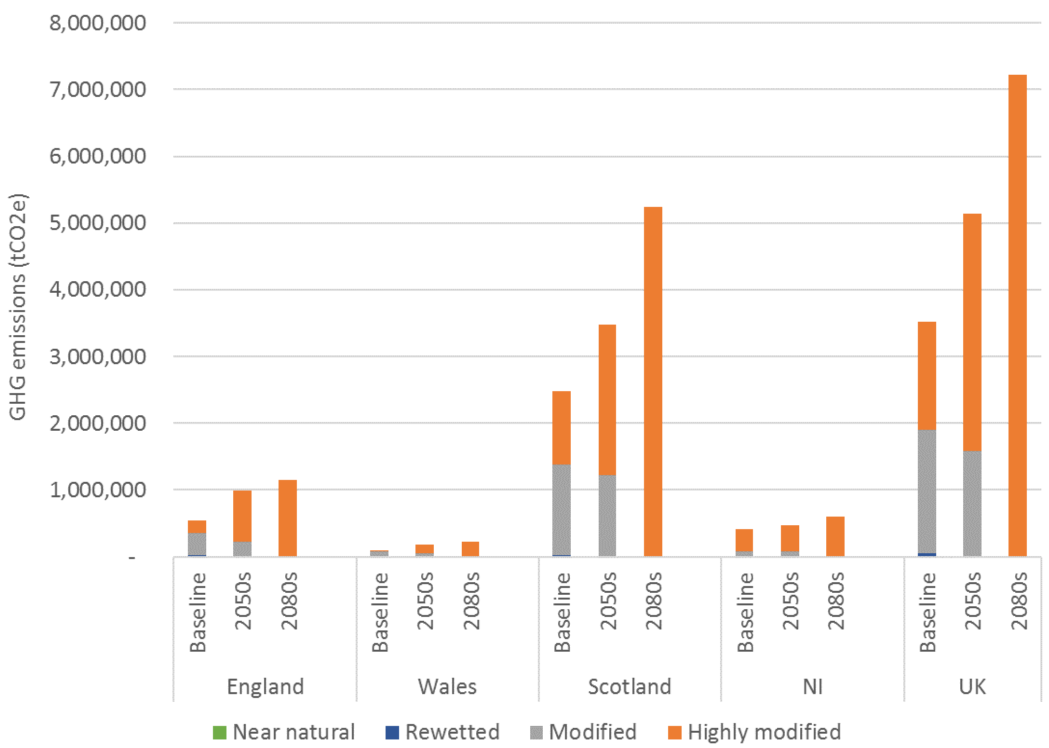



*Figure 34.* ***GHG emissions ($tCO_2e$) from peatlands by UK country and by condition category, under RCP8.5 pathway, for baseline, 2050s and 2080s****, for median of a) thirteen CMIP5 ensembles and b) fifteen PPE ensembles.*

The costs of carbon emissions are summarised in Table 60 and in Figure 35. At UK level, annual average costs rise from £210 million at baseline (present day), to around £1.3 billion in the 2050s, at which point the climate ensembles diverge. In the 2080s, costs in the CMIP5 ensembles total £1.7 billion, while in the PPE ensembles the costs total £2.4 billion. The majority of the costs occur in Scotland due to the extensive peatland habitats located there. Future costs increase partly due to the increase in peatland area falling into the highly modified category, but also because future carbon prices increase dramatically over time due to stringent mitigation targets later in the century.

*Table 60. **Annual cost of GHG emissions due to exceedance of 30-year mean temperature of warmest month threshold (£ million) under RCP8.5 pathway, for baseline, 2050s and 2080s**. for median of a) thirteen CMIP5 ensembles and b) fifteen PPE ensembles.*

| **Region** | **CMIP5** | | | **PPE** | | |
|---|---|---|---|---|---|---|
| | Baseline (1990 - 2019) | 2050s (2040-2069) | 2080s (2070-2099) | Baseline (1990 - 2019) | 2050s (2040-2069) | 2080s (2070-2099) |
| England total | 32.9 | 202.4 | 341.3 | 32.9 | 260.6 | 395.8 |
| Wales total | 4.6 | 47.9 | 76.6 | 4.6 | 47.9 | 76.6 |
| Scotland total | 148.1 | 911.1 | 1,193.0 | 148.1 | 911.1 | 1,794.0 |
| Northern Ireland total | 24.6 | 125.0 | 163.7 | 24.6 | 125.0 | 206.9 |
| **UK total** | **210.2** | **1,286.4** | **1,774.6** | **210.2** | **1,344.7** | **2,473.3** |

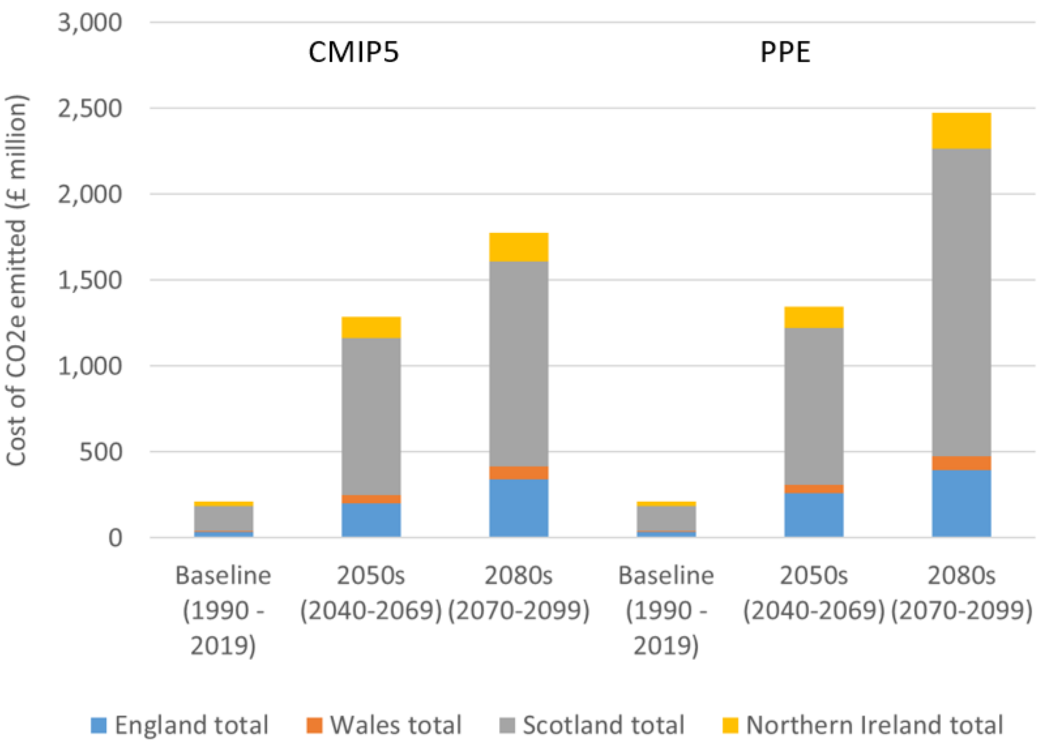



*Figure 35. **Annual cost of GHG emissions due to exceedance of 30-year mean temperature of warmest month threshold, by country (£ million), under RCP8.5 pathway, for baseline, 2050s and 2080s**. for median of a) thirteen CMIP5 ensembles and b) fifteen PPE ensembles.*

**Is there a risk of irreversible change in the ecosystems affected, or substantial time lags in recovery?**

The evidence suggests that peatlands will be more resilient to climatic pressures if they are in good condition, and may indeed be able to self-adapt (e.g. through changing their vegetation species mix) to continue functioning, up to a point. This autonomous adaptation may nonetheless lead to a change in ecological condition (with significant vegetation change), or an adverse change in the amount and type of ecosystem services provided by the peatlands. Timescales for recovery can vary considerably, ranging from decades to centuries, and true recovery may not be possible for peatlands with extensive and deep gullying.

**What is the impact of current levels of adaptation at mitigating these risks?**

Local projects are making progress with efforts to maintain peatlands; around 110,000 ha (5% of total) of UK peatland are estimated to have undergone some form of restoration between 1990 and 2013, of which 73,000 ha involved re-wetting (Evans et al., 2017). Rates of peat restoration have increased since 2013 as a result of recent funding initiatives, notably the Scottish Government's Peatland Action programme and Defra peat restoration fund, as well as a number of large peatland-focused EU LIFE projects. Despite this, the percentage of upland bogs in SSSIs which are in favourable condition, according to UK reporting on habitat condition under Article 17, has decreased from 19% in 2003 to 12% in 2018 (CCC, 2019). See also details in Table 38.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Up to a point, a functioning peatland which is in good condition will have some resilience to temperature change and drought impacts. Therefore, improving the condition of peatlands can reduce the risks associated with reaching the threshold. Actions such as raising the water table, and management interventions such as changes in grazing and burn management, can be taken to reduce the loss of peatland. In the most extreme areas of degradation (e.g. active erosion gullies) more substantial interventions such as dam construction and active revegetation may be required. These actions could be taken in advance to reduce the risk of peatland being lost. However, damage to peatlands is difficult and expensive to reverse at best, and may be irreversible at worst. Adaptive management responses will be more effective if they can be undertaken before climate thresholds have been crossed. However, this is difficult for much of the UK since temperature assessment against the climate envelope suggests that the majority of England, Wales and Northern Ireland is already above or close to the threshold. Active restoration of degraded peatland and sustainable management of existing peatland will be a crucial component of working towards the Government's target of Net Zero by 2050 (CCC 2020). See also details in Table 38.

**In what scenarios are there limits to adaptation?**

Potentially irreversible degradation of peatlands can occur if peat dries out to the extent that it becomes hydrophobic, as the structurally altered peat will not re-wet. Gully erosion also presents a major challenge for peat restoration, because it fundamentally alters the topography and hydrology of peatlands, which form in areas of low relief over millennia. Mitigation measures can delay the point at which a climatic threshold is crossed, however, once the threshold has been crossed there is a risk of the peatland becoming irreversibly damaged, at which point no adaptation can be undertaken to rectify this.

At present, many adaptation actions are largely implemented through voluntary actions within agri-environment schemes, which can limit uptake. Measures such as raising the water table and constructing dams require a catchment approach, which may present coordination challenges.

# 13 Managed woodlands – Case study: Climatic moisture deficit and temperature impacts on productivity (oak, broadleaves and conifers)

This case study builds on the screening assessment by incorporating a wider set of climate projections into the analysis. It calculated climate moisture deficit separately from each set of model ensembles (see Case Study Methods section), and then selected the median performing ensemble to run the analysis. The case study calculates the effect of future extreme warm and dry periods over decadal periods on oak, broadleaved and conifer woodlands at a National Forestry Inventory (NFI) regional scale.

Reduced moisture availability occurring above a climatic moisture deficit of 200 mm for drought-sensitive species and 300 mm for drought-tolerant species (occurring in ≥ 5 years in 10) has negative impacts on tree growth. Warmer summers with a monthly mean of daily maximum temperature above 25 °C have also been shown to reduce timber quality in certain tree species. In combination, these effects result in reduced tree growth, but particularly lower timber quality, with impacts on timber production. These impacts are summarised in Table 61 and Figure 36 below.

*Table 61. **Potential threshold-driven impacts in woodlands***

| Climate-mediated stressor | Habitat | Threshold | Biophysical response | Societal end-point affected | Aligned risk descriptors |
|---|---|---|---|---|---|
| Temperature | Oak – other broadleaved and conifer woodland | Mean decadal summer month (June July August) maximum temperature > = 35$^{0}$C | Biotic tree stress, leaf loss, growth reduction in following years, abiotic pest and pathogen infection | Carbon sequestration, timber quality, | Ne 7 |
| Temperature + drought | Oak – other broadleaved and conifer woodland | Climatic Moisture deficit (CMD) >200 mm drought sensitive species >300mm drought tolerant species; | Biotic tree stress, leaf loss, cambium cracks, growth reduction in following years, abiotic pest and pathogen infection | Carbon sequestration, timber quality | Ne 7 |

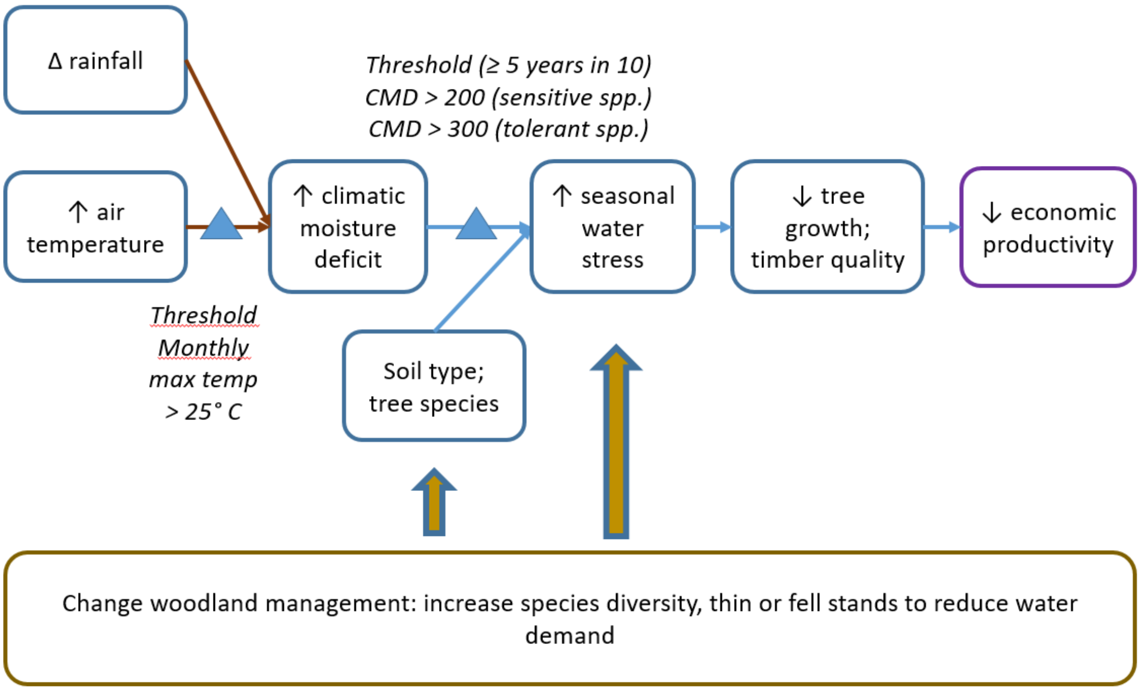



*Figure 36. **Impact chain showing the effect of increased temperature and summer drought on oak woodlands**. Purple box shows social/economic or biodiversity endpoint; Brown box shows potential adaptation measures*

**What climate hazard thresholds represent points beyond which the effective functioning of key systems within the natural environment may be compromised, and why?**

A monthly mean of daily maximum temperature above 25 °C and climatic moisture deficit of 200 mm for drought-sensitive species and 300 mm for drought-tolerant species (occurring in ≥ 5 years in 10), lead to impacts on tree growth and timber quality (Allen et al., 2015; Green and Ray, 2009). Allen et al (2015) conclude: droughts will occur across the UK due to increasing climate variability. Phenological changes under higher temperatures (longer growing season) can compensate little for the synergistic impact of temperature and soil dryness during severe droughts as demonstrated in a study by Dolschak et al. (2019) for beech (*Fagus sylvatica*). In this case study we consider three forms of timber production as distinct categories in terms of both management and economic value for the UK timber industry. These categories are: oak (*Quercus robur & Q. petraea*) other broadleaf, and conifer.

This case study focuses on the summer temperature and drought impacts. Here we use a combination of the magnitude of predicted change in species suitability under climate change, combined with site types vulnerable to greater seasonal changes in the soil water regime. The assessment is run at the level of National Forest Inventory (NFI) regions (Figure 17) and aggregated to climate regions.

We first calculated climatic moisture deficit for all 23 ensembles in the PPE and the CMIP5 ensemble set, and selected the median performing ensembles from PPE and CMIP5 to use in the woodland modelling. PPE ensemble member 3 and CMIP5 ensemble member 21 projections from UKCP18 RCP 8.5 were selected to assess the projected trends in climate change that might increase abiotic impacts on oak, mixed broadleaved and conifer woodlands. For a reference location in each region (NFI regions) we calculated:

- the change in mean decadal temperature;
- the number of years per decade the summer monthly mean maximum temperature > 25 °C; and
- the number of years per decade the climatic moisture deficit (CMD) is greater than 200mm and 300mm for drought-sensitive and drought-tolerant species respectively.

The CMD is the accumulated maximum excess of monthly potential evaporation over monthly precipitation ($Et_0 - P$) in mm, where $Et_0$ was calculated using the Hargreaves model in the SPEI R-package.

We estimated the proportion of three broad woodland habitat types - oak, broadleaved and conifer woodland using the published standing volumes of woodlands by age class described regionally according to the National Forest Inventory (NFI). Oak monoculture is treated as its own class, since single-species oak stands are managed differently to mixed broadleaf stands. Mature age classes of oak and broadleaved woodland will have passed the point of maximum mean annual increment (MMAI), and an assumption was made that the impact of climate change on oak and broadleaved yield will be small under climate change. However, a yield reduction was applied to conifer stands of 80-100% of current yield (determined from expert opinion based on the Ecological Site Classification yield model predictions from NFI regions in Britain) varying by climate change severity according to NFI region. For all three woodland types we assumed that the impact of climate change - extreme years of heat and drought - would cause stress leading to wood structural damage, biotic impacts - and this study shows it could cause large affects and economic loss from low wood quality, compared to small losses in yield. Therefore, the model adjusts the assortment of wood products according to the degree of climate change exposure in each NFI region.

Trees respond to extreme heat or extreme drought in different ways. Oak and broadleaved trees may shed leaves to reduce transpiration, although often in response to partial xylem embolism that may affect the tree into the future for many years. Conifers may also shed needles, and in drought stressed Sitka spruce the stem may crack due to embolism and xylem failure. The climatic thresholds under which damage occurs are not precisely known. An average monthly maximum temperature threshold of 25 °C would require several daily maximum temperatures in excess of 30 °C, causing heat damage to species that are not adapted or acclimated to such high summer temperatures. For drought sensitive species (non-adapted to moisture stress), a maximum annual climatic moisture deficit (CMD) of 200 mm would cause a proportion of trees in a stand to suffer stress and structural damage. Successive years of high CMD would increase the proportion of damaged trees in a stand, likely leading to mortality. Britain's two most common conifer species (Sitka Spruce and Scots pine) fall into this category. Douglas-fir is more drought tolerant and the threshold of 300 mm CMD was applied. For broadleaved species the CMD of 300 mm was applied to oak, beech and sycamore.

A time series analysis of the UKCP18 from the PPE ensemble member 3 climate projection shows high CMD exceedance of 200 mm and 300 mm thresholds in the south and east of Britain (Table 62a&b); East England, South-East England, South-West England, and East Midlands. In these regions CMD 200 mm is exceeded 85% of years and CMD 300mm is exceeded over 50% of years in the century from 1991 to 2090, with a trend of increasing frequency of extreme events per decade into the future. Table 62a&b also demonstrate a decreasing trend in the frequency of exceedance moving north and west in Britain, with occasional exceedance occurring in the later decades of the 21st century as far north as East and North-East Scotland. West Scotland and North Scotland remain below the exceedance thresholds through the century.

The same decadal frequency time series, for CMD 200 mm and 300 mm thresholds, was calculated for CMPI5 ensemble member 21 (Table 63a&b). Exceedance frequency is greater than PPE projections for the two southern and eastern regions: East England, South-East England, and is spread more evenly through the decades. For South-West England and all the other more northerly regions the frequency decreases considerably moving northwards within the UK.

A similar analysis was performed for temperature, using the summer monthly average maximum temperature of the same selected locations in each forestry region (National Forest Inventory regions), shown in Table 64 for a threshold temperature of 25 °C, using PPE. In East England and South-East England climate projections indicate 50% of years between 1991 - 2090 will have summer months where the monthly average maximum temperature exceeds 25 °C. The PPE ensemble 3 projection indicates a rapid increase in the frequency of decadal exceedance after 2051 in the southern regions of England. In northern England, Wales the frequency of exceedance will begin to rise above the threshold after 2015, and in Scotland the temperature threshold will be exceeded very rarely through the 21st century.

Table 65 shows the frequency by decade and NFI region, of monthly average maximum temperature exceeding 25 °C, using CMIP5. Compared to Table 64, the CMIP5 ensemble projections indicate lower temperatures and fewer years per decade of 25 °C exceedance. Compared to PPE projections the CMIP5 member 21 indicates half the years exceeding 25 °C for the two southern regions of England, and considerably fewer years of exceedance for regions further north and west. In northern England and Scotland CMIP5 shows no 25 °C exceedance years through the century.

**What are the resulting impacts on the goods and services provided to society from the natural environment? What would be the quantified impact?**

Large parts of England will show reduced growth of oak and other broad-leaved trees. Conifers will be less affected. In particular, East England, South East England, South West England and the Midlands with larger stocks of oak and broadleaved woodlands are likely to experience widespread drought causing physiological damage to trees (drought cracks and shake). The carbon sequestration service of affected stands will also be reduced, since hotter drier summers reduce annular growth ring increments, and this physiological impact has been shown to last over a decade. Recent studies have shown that the extreme impacts of climate change on European beech occur across its range (Hacket-Pain et al. 2016), and this has been reported in the New Forest (Mountford & Peterken, 2003) and in Lady Park Wood (Peterken and Mountford, 1996) following the 1975-76 drought in Britain.

*Table 62.* ***Frequency of CMD threshold exceedance by decade for the 14 National Forest Inventory regions of Britain for a) greater or equal to 200 mm b) greater or equal to 300 mm, for PPE projections under RCP8.5 pathway.*** *Data calculated from the UKCP18 PPE ensemble member 3.*

**a) CMD >=200mm**

| Decade | East England | South East England | South West England | East Midlands | West Midlands | Yorkshire & Humber | Wales | North East England | North West England | South Scotland | East Scotland | North East Scotland | West Scotland | North Scotland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1991-2000 | 6 | 5 | 4 | 6 | 5 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2001-2010 | 8 | 8 | 7 | 6 | 5 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2011-2020 | 7 | 6 | 7 | 8 | 7 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2021-2030 | 10 | 9 | 9 | 9 | 8 | 4 | 4 | 2 | 2 | 0 | 0 | 0 | 0 | 0 |
| 2031-2040 | 6 | 7 | 8 | 8 | 6 | 3 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2041-2050 | 9 | 9 | 8 | 9 | 8 | 6 | 4 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2051-2060 | 9 | 10 | 9 | 9 | 9 | 6 | 6 | 5 | 3 | 0 | 0 | 0 | 0 | 0 |
| 2061-2070 | 10 | 10 | 10 | 10 | 10 | 9 | 8 | 5 | 4 | 1 | 2 | 2 | 0 | 0 |
| 2071-2080 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 9 | 7 | 2 | 4 | 4 | 0 | 0 |
| 2081-2090 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 9 | 7 | 2 | 5 | 5 | 0 | 0 |
| Total | 85 | 84 | 82 | 85 | 78 | 54 | 48 | 36 | 24 | 5 | 11 | 11 | 0 | 0 |

**b) CMD >=300mm**

| Decade | East England | South East England | South West England | East Midlands | West Midlands | Yorkshire & Humber | Wales | North East England | North West England | South Scotland | East Scotland | North East Scotland | West Scotland | North Scotland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1991-2000 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2001-2010 | 3 | 4 | 2 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2011-2020 | 2 | 3 | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2021-2030 | 4 | 3 | 5 | 4 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2031-2040 | 4 | 5 | 2 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2041-2050 | 6 | 5 | 5 | 5 | 4 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2051-2060 | 9 | 9 | 7 | 9 | 7 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2061-2070 | 9 | 9 | 9 | 9 | 9 | 5 | 6 | 3 | 2 | 0 | 0 | 0 | 0 | 0 |
| 2071-2080 | 10 | 10 | 10 | 10 | 10 | 10 | 8 | 6 | 4 | 0 | 0 | 0 | 0 | 0 |
| 2081-2090 | 10 | 10 | 10 | 10 | 10 | 8 | 8 | 4 | 3 | 0 | 1 | 1 | 0 | 0 |
| Total | 58 | 59 | 53 | 55 | 47 | 29 | 26 | 13 | 9 | 0 | 1 | 1 | 0 | 0 |

*Table 63.* ***Frequency of CMD threshold exceedance by decade for the 14 National Forest Inventory regions of Britain for a) greater or equal to 200 mm b) greater or equal to 300 mm, for CMIP5 projections, under RCP8.5 pathway.*** *Data calculated from the UKCP18 CMIP5 ensemble member 21.*

**a) CMD >=200mm**

| Decade | East England | South East England | South West England | East Midlands | West Midlands | Yorkshire & Humber | Wales | North East England | North West England | South Scotland | East Scotland | North East Scotland | West Scotland | North Scotland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1991-2000 | 10 | 8 | 3 | 3 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2001-2010 | 10 | 10 | 8 | 6 | 4 | 6 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 |
| 2011-2020 | 7 | 6 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2021-2030 | 8 | 6 | 3 | 4 | 2 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2031-2040 | 10 | 10 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2041-2050 | 8 | 7 | 6 | 4 | 3 | 4 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2051-2060 | 10 | 10 | 6 | 6 | 1 | 3 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| 2061-2070 | 10 | 9 | 6 | 5 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2071-2080 | 10 | 10 | 7 | 7 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2081-2090 | 10 | 7 | 7 | 6 | 3 | 3 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| Total | 93 | 83 | 47 | 45 | 16 | 20 | 9 | 2 | 6 | 0 | 0 | 2 | 0 | 0 |

**b) CMD >=300mm**

| Decade | East England | South East England | South West England | East Midlands | West Midlands | Yorkshire & Humber | Wales | North East England | North West England | South Scotland | East Scotland | North East Scotland | West Scotland | North Scotland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1991-2000 | 6 | 3 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2001-2010 | 8 | 7 | 3 | 4 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2011-2020 | 4 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2021-2030 | 4 | 3 | 2 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2031-2040 | 7 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2041-2050 | 5 | 4 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2051-2060 | 6 | 5 | 4 | 3 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2061-2070 | 8 | 5 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2071-2080 | 8 | 8 | 3 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2081-2090 | 7 | 6 | 3 | 3 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 63 | 49 | 25 | 19 | 2 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*Table 64.* ***Frequency of monthly average maximum temperature exceeding 25$^0$C by decade for the 14 National Forest Inventory regions of Britain, for PPE projections, under RCP8.5.*** *Data calculated from the UKCP18 PPE ensemble member 3*

| Decade | East England | South East England | South West England | East Midlands | West Midlands | Yorkshire & Humber | Wales | North East England | North West England | South Scotland | East Scotland | North East Scotland | West Scotland | North Scotland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1991-2000 | 2 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2001-2010 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2011-2020 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2021-2030 | 2 | 2 | 2 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2031-2040 | 2 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2041-2050 | 5 | 5 | 3 | 4 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2051-2060 | 8 | 8 | 7 | 7 | 5 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2061-2070 | 9 | 9 | 7 | 8 | 6 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | 0 |
| 2071-2080 | 10 | 10 | 10 | 10 | 10 | 8 | 7 | 3 | 4 | 0 | 0 | 0 | 0 | 0 |
| 2081-2090 | 10 | 10 | 10 | 10 | 10 | 8 | 8 | 4 | 6 | 0 | 0 | 0 | 0 | 0 |
| Total | 50 | 49 | 39 | 43 | 34 | 19 | 18 | 9 | 12 | 1 | 1 | 1 | 0 | 0 |

*Table 65.* ***Frequency of monthly average maximum temperature exceeding 25$^0$C by decade for the 14 National Forest Inventory regions of Britain, for CMIP5 projections, under RCP8.5.*** *Data calculated from the UKCP18 CMIP5 ensemble member 21*

| Decade | East England | South East England | South West England | East Midlands | West Midlands | Yorkshire & Humber | Wales | North East England | North West England | South Scotland | East Scotland | North East Scotland | West Scotland | North Scotland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1991-2000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2001-2010 | 4 | 4 | 2 | 2 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2011-2020 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2021-2030 | 2 | 2 | 2 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2031-2040 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2041-2050 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2051-2060 | 4 | 4 | 3 | 2 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2061-2070 | 5 | 5 | 2 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2071-2080 | 6 | 6 | 3 | 2 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 26 | 26 | 12 | 9 | 7 | 2 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Stressed trees will also be more vulnerable to pest and pathogen damage (Tubby and Webber, 2010): oak dieback (England and Netherlands 1921 drought – Gibbs and Greig, 1997), beech decline (Hacket-Pain et al. 2016), damage to conifers: bark beetles (Seidl et al., 2017), stem cracks (Green and Ray, 2009).

In summary, climate change projections indicate spatial and temporal variation across Britain. As summers become warmer and drier in the south and east of England many species will reduce biomass production. In East and South-East England, oak and broadleaved woodland is more widespread than conifer woodland, and these woodland types will be under severe drought stress under projected climates of both PPE and CMIP5. The main production conifer species are generally suited to current sites in the north and west of Britain and will be less impacted by climate change. Many conifer species in the north and west will benefit from warmer summers and produce an increased percentage biomass. However, the stochastic nature of extreme drought will always be present, and despite projected increased yields, the risk of drought damage and associated wood quality impact remains.

No further economic analysis of these impacts is reported here.

**Is there a risk of irreversible change in the ecosystems affected, or substantial time lags in recovery?**

Trees are generally long-lived species; oak and broadleaved trees can live for hundreds of years. Managed oak and broadleaved woodlands typically have a rotation length of a hundred years or more (for oak). The continuity of woodland conditions through tree growth, thinning cycles and harvesting to regeneration and a continuation of this cycle maintain the woodland ecosystem. Managed woodlands in the south of England are likely to be adversely affected by climate change due to more frequent and severe summer drought conditions and wetter milder winters, causing reductions in yield and reductions in timber quality from drought cracking (Field et al. 2019; Sinclair et al. 2015). Timber quality damage is irreversible, reducing timber value of stems at harvesting. Although trees may recover from slight drought stress over several years, severe drought stress may increase subsequent tree mortality for many years, e.g. 15 years for beech after the 1976 drought in Lady Park Wood (Peterken and Mountford, 1996).

**What is the impact of current levels of adaptation at mitigating these risks?**

The forestry sector is very slow to respond to the issues of climate change. The public sector is perhaps more engaged in adaptation management planning. This takes the form of checking species suitability in future climates using Ecological Site Classification (Pyatt et al., 2001), adjusting species choice and making more use of mixed species woodland in planning. However, cascading effects in biodiversity and the susceptibility of exotic provenances to native disease strains are still being assessed. The private sector appears to be less concerned as Sitka spruce is better situated in the north and west of Britain where the consequences of abiotic damage are projected to be less pronounced. Biotic damage from pests and pathogens is the main concern in production forestry.

There is research also focusing on adaptive traits and phenotypic plasticity to select tree genotypes that are better suited to the future climate (Saenz-Romero et al. 2017).

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

In woodland management, the view is typically long-term and management is adaptive. In advance of timber quality being impacted early felling and replacement are the most likely options for climate risk stands. There are more options for new plantations and restocking. Tolerances of future conditions of more frequent and longer droughts, warmer temperatures, but also water-logging during winter months and spring varies between tree species, but also tree lineages (provenances) within species. There may be scope to consider adaptive potential where periods of drought act as drivers of selection that would leave the UK stock with more drought-tolerant genotypes. Seed selection of pre-adapted provenances could also facilitate adaptation. Research in areas of assisted diversification, provenance/progeny trials from UK populations, and building genetic resources will improve the ability to provide seed material a wider range of phenotypic variance and tolerance to future conditions within native species (Cannon & Petit, 2019). Fundamentally, however, it will be a better matching of species requirements to the correct habitat and site conditions to make the stands more resilient for future planting schemes.

**In what scenarios are there limits to adaptation?**

Alternative tree species for commercial planting under any climate conditions are potentially available, but it will take time to replace existing stock. Acceptance by foresters to adopt these species for planting, and acceptance of different products by timber users may limit the speed of adaptation.

# 14 Marine and Coastal margins - Case study: Temperature effects on naturalisation of the Pacific oyster *Magallana gigas*

This case study builds on the screening assessment by mapping impacts spatially, and showing the trajectory of impacts over time. In contrast to the other assessments, the climate data for the screening assessment and the case study are the same (see section 9.4).

Figure 37 summarises the threshold and impacts from naturalisation of the Pacific oyster, *Magallana gigas* (previously *Crassostrea*), in the United Kingdom. Bottom temperatures where > 825 degree days above 10.55 °C lead to increased spawning (see section 9.4.1), while growth rates are governed by an optimum bottom temperature of 20 – 25 °C, leading to faster growth and an expansion of their current range.

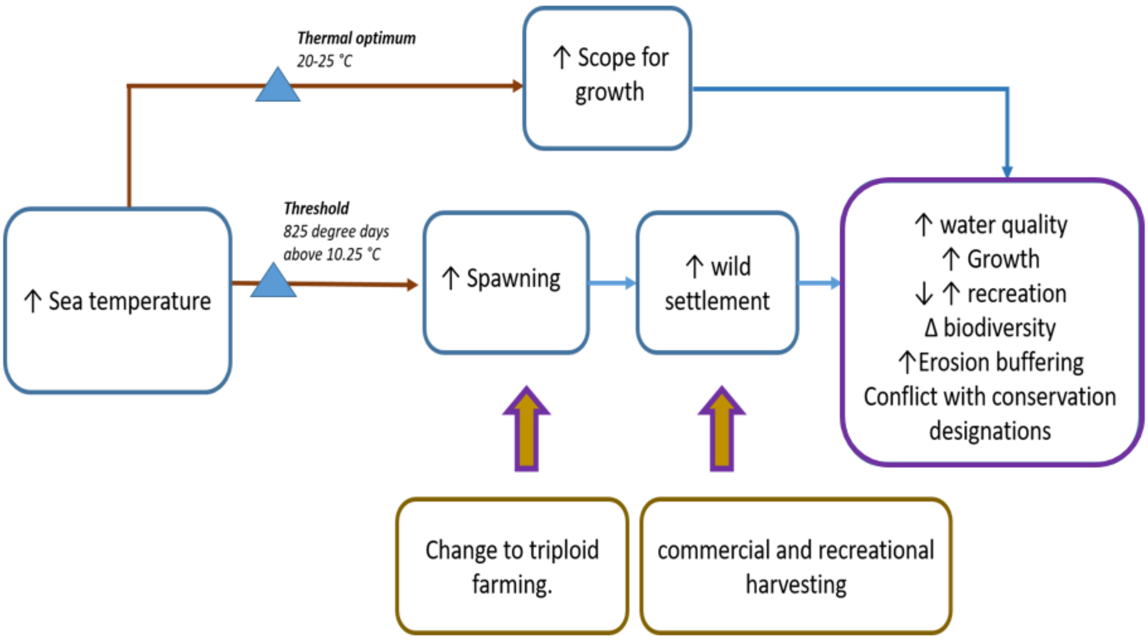



*Figure 37.* ***Impact chain for temperature effects on naturalisation of the Pacific oyster, Magallana gigas****. Temperatures are sea bottom-temperature. Purple box shows social/economic or biodiversity endpoint(s). Brown boxes shows potential adaptation measures.*

**What climate hazard thresholds represent points beyond which the effective functioning of key systems within the natural environment may be compromised, and why?**

The threshold for spawning of *M. gigas* is 825 degree days for a daily mean bottom temperature of 10.55 °C. *M. gigas* was introduced to the NE Atlantic under the premise that water temperatures were suitable for growth but too cold for successful completion of its life cycle, and as such, naturalisation was not expected. Recent warming trends have changed this (e.g. Spencer et al., 1994). Summer temperatures in much of continental Europe now facilitate spawning and settlement and wild *M. gigas* populations can be found in areas far away from aquaculture sites. Currently, *M. gigas's* naturalisation frontier is along England's SE coast where it can be found in high abundances forming extensive reefs

(Thomas et al., 2016). This research indicates UK seawater temperatures are projected to rise considerably over the coming decades. On average, temperatures at the seabed are estimated to increase by 0.9 °C by 2040 – 2049 and 2.0 °C by 2070 – 2089 in UK waters (see Table 45 in Section 9.4.3), with the largest increases taking place in the coastal waters off England and Wales, although all parts of the UK are affected by the 2080s (Figure 38, Figure 39). These temperature increases will result in settlement thresholds being exceeded at higher latitudes towards the end of the century resulting in a northward shift of the potential settling grounds of *M. gigas*. Increased temperatures will also push *M. gigas* towards its growth optimum of 20 - 25 °C bottom temperatures (King, 1977; Brown and Hartwick, 1988; Shpigiel and Blaylock, 1991).

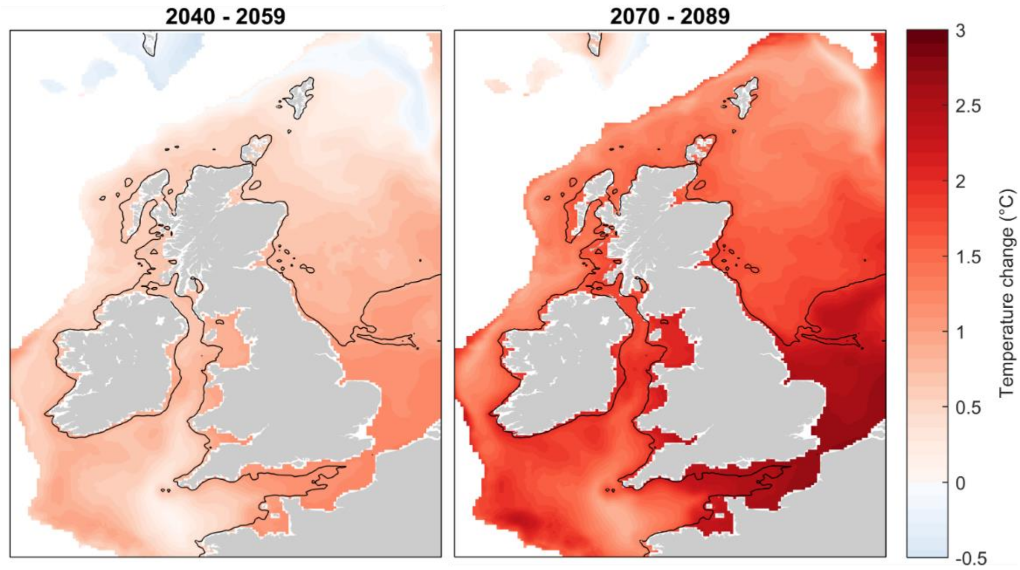



*Figure 38.* ***Predicted bottom temperature (up to 350 m water depth) change in 2050s and 2080s compared to baseline period (2000 - 2019), under RCP8.5.*** *Black contour indicates maximum depth of M. gigas (50 m water depth).*

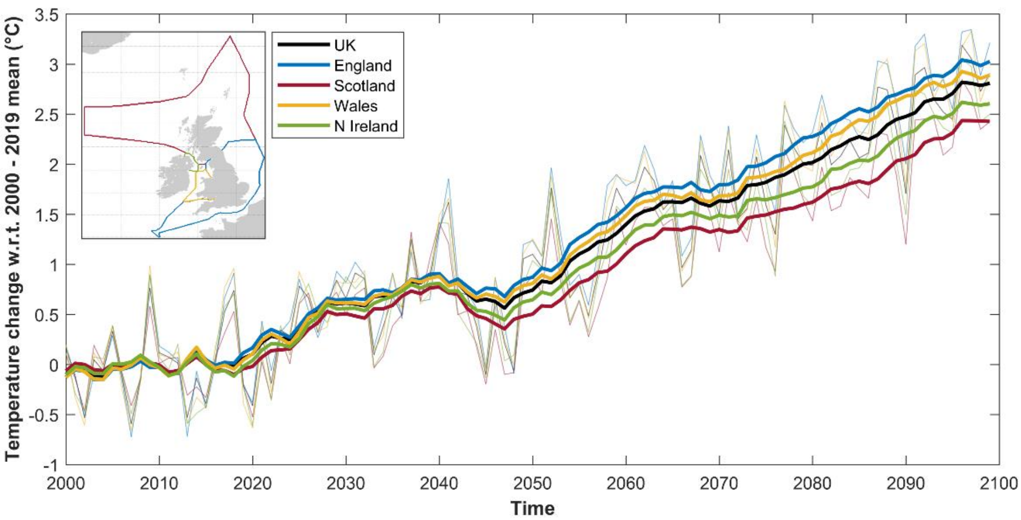



*Figure 39*. **Bottom temperature change compared to 2000-2019 baseline (up to 50 m water depth).** Thin line shows unsmoothed data, thick line data smoothed with a 10 year running mean). Insert shows marine country boundaries.

We determined the proportion of years where these settlement thresholds are exceeded for the baseline, 2050s and 2080s. We also quantified the total viable area where thresholds are exceeded up to 2100. We limited all quantifications of suitable habitat and area to 50 m that represents the maximum depth for *M. gigas.*

*Expansion of potential settlement area*

Over the baseline period (2000 – 2019) settlement thresholds were regularly exceeded (>7/10 years) as far north as Cardigan Bay in Wales and the Wash estuary in England. Infrequent exceedance (< 2/10 years) was observed as far north as the Solway Firth in Scotland. Our projections suggest a considerable poleward expansion that encompasses much of the north coasts of England and west coast of Scotland between 2070 — 2089 (Figure 40 and Figure 41**Error! Reference source not found.**). Taken as a whole, this represents a 331 % increase in suitable settlement area for the UK (see Table 46 in Section 9.4.4). Greatest gains in suitable area were observed in England (124,000 km$^2$ by 2100), which was driven predominantly by large areas of the shallow North Sea around Dogger Bank. Scotland saw the largest proportional increase in suitable area by the 2080s driven by large increases in suitable habitat in the Inner Hebrides.

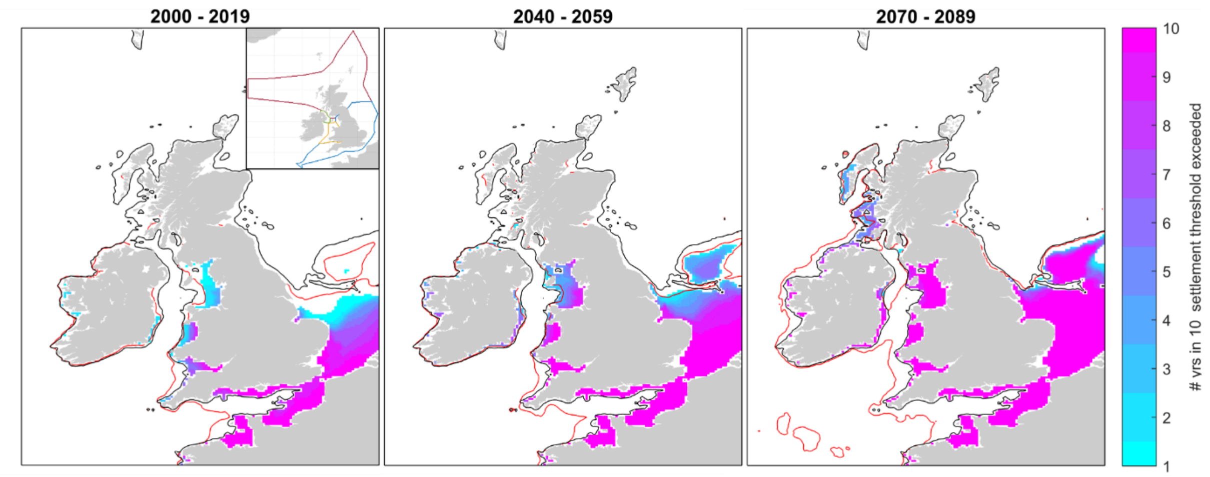



*Figure 40.* ***Number of years per decade settlement threshold is exceeded for M. gigas, for baseline, 2050s and 2080s, under RCP8.5****. Red line indicates exceedance of 18 °C throughout the year. Black line is maximum depth of M. gigas (50 m water depth). Insert shows marine boundary used for calculations.*

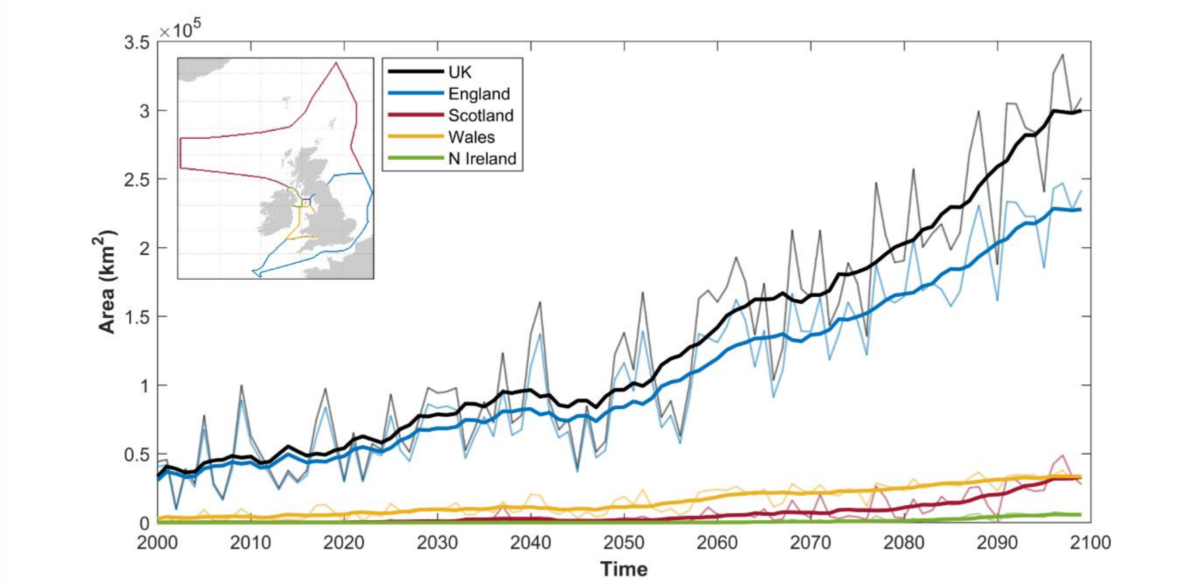



*Figure 41. **Area of viable seabed for spawning of M. gigas under RCP8.5**. Thin line shows unsmoothed data, thick line data smoothed with a 10 year running mean) for M. gigas settlement. Data calculated to 50 m depth range for M. gigas (refer Figure 38 for this boundary). Insert shows country boundaries used for calculations.*

**What are the resulting impacts on the goods and services provided to society from the natural environment? What would be the quantified impact?**

The greatest concerns for *M. gigas* naturalisation have been the potential for conflict with native species and habitats. *M. gigas* can completely transform intertidal systems (Ruesink et al., 2005). This has the potential to compromise protected habitats (Herbert et al., 2016). For example, intertidal rocky reefs and mudflats that can be transformed into oyster reefs are Annex 1 habitats of the EU Habitats Directive. Some reefs are forming on England's southern coast, e.g. in Kent (Herbert et al. 2012; 2016). Reef formation can also conflict with other commercially important bivalves. The blue mussel, *Mytilus edulis,* supports large fishery and mariculture enterprises in the UK. *M. gigas* can almost completely replace *M. edulis*, reaching densities of up to 2000 per $m^2$ (Markert et al., 2013) and can also reduce the local carrying capacity for nearby cultivated mussels (Wijsman et al., 2008). More recently, there has been concerns over competition with the native oyster, *O. edulis* (Zwerschke et al., 2018) that is undergoing massive restoration efforts across Europe.

The majority of impacts caused by this non-native species on biodiversity are negative (see Table 47). However, there is recognition that *M. gigas* also delivers a number of ecosystem goods and services that directly impact human society, including both positive and negative aspects. Positive benefits include improving water quality, improved wave attenuation with benefits for coastal defence, and the potential to harvest them for food. Negative impacts include reduced amenity value of beaches due to sharp shells on reefs causing a hazard to swimmers, surfers and other beach users.

**Is there a risk of irreversible change in the ecosystems affected, or substantial time lags in recovery?**

In early stages of naturalisation culling small populations, before reefs form, may be possible (Guy and Roberts, 2010). However, once established, the only way to prevent further spreading will be to implement widespread eradication schemes. This will be very labour intensive and need to be conducted over successive years to make sure any remaining brood stock is removed. An alternative may be to establish a commercial fishery which would serve as a cost effective way of reducing populations while also maintaining the livelihood of coastal communities.

**What is the impact of current levels of adaptation at mitigating these risks?**

Currently the adaptation of *M. gigas* naturalisation in the UK is low as naturalisation is predominantly limited to SW England. Culling trials have been conducted in the UK. In Strangford Loch, Northern Ireland, where abundances are very low (< 1 per $m^2$) and settlement thresholds are rarely exceeded, mechanical removal seems successful (Guy and Roberts, 2010). In southeast England, where extensive reefs are found, a pilot trial was conducted in 2015. However, resurveys of culled areas have not yet been conducted (McKnight and Chudleigh, 2015). Exploitation is another option and a dredge fishery operates in the Blackwater Estuary, Essex for both *M. gigas* and *O. edulis.* Here, handpicking of seed in the estuary also prevents widespread reef formation.

**What additional adaptation management options could be undertaken, either in advance to reduce the risk of these thresholds occurring, or afterwards to manage the impacts?**

Having pre-emptive rapid action plans in place for sites where *M. gigas* settlement will compromise the sites conservation status, may prevent settlement turning into reefs that cannot then be removed.

Pre-emptively moving to triploid farming in areas anticipated to exceed settlement thresholds in the future, may work as triploids are sterile. They have the added benefit of being saleable all year round compared to diploids that are in poor condition after spawning.

The adaptation response to the spread of *M. gigas* may be different in parts of the UK or over time as our understanding, especially of impacts, improves.

**In what scenarios are there limits to adaptation?**

The connected nature of marine environments and *M. gigas's* high dispersal capacity mean larvae can easily cross geographical and geopolitical boundaries. Moreover, any management interventions enacted on anything but an international scale may be severely compromised. For example, established populations in SW England are likely a result of immigration from French, rather than neighbouring English, populations (Lallias et al., 2013).

There have been reports that triploid cells are not stable, with reversion back to diploids over time. On top of this, triploids can have mosaic cells (up to 20%) that also contain diploid cells (Allen et al., 1999). Therefore, switching to triploids may not prevent naturalisation. Triploid seed costs more than diploids and many farmers may be reluctant/unable to pay extra. In addition, some food producers may wish to avoid using triploid stock as it may be termed "genetically modified" with associated negative connotations with consumers.

# 15 References


Abbott K.A., Taylor M., and Stubbings L.A (2012) SUSTAINABLE WORM CONTROL STRATEGIES FOR SHEEP 4th Edition, https://www.scops.org.uk/workspace/pdfs/scops-technical-manual-4th-edition-updated-september-2013.pdf

Abela, A., Hamilton, L., Hitchin, R. and Pout, C. (2016) Study on Energy Use by Air-Conditioning: Annex D: Monitored Consumptions. London.

Adams, C.E., Lyle, A.A., Dodd, J.A., Bean, C.W., Winfield, I.J., Gowans, A.R., Stephen, A. and Maitland, P.S., 2014. Translocation as a conservation tool: case studies from rare freshwater fishes in Scotland. Glasgow Naturalist, 26 (Part 1), pp.17-24.

ADAS (2013) Economic Impact of Health and Welfare Issues in Beef Cattle and Sheep in England, http://beefandlamb.ahdb.org.uk/wp-content/uploads/2013/04/Economic-Impact-of-Health-Welfare-Final-Rpt-170413.pdf

ADAS (2014) Impact of 2014 Winter Floods on Agriculture in England, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/401235/RFI7086_Flood_Impacts_Report__2_.pdf

AHDB (2015) Managing cattle and sheep during extreme weather events, https://projectblue.blob.core.windows.net/media/Default/Imported%20Publication%20Docs/BRP-Managing-cattle-and-sheep-during-extreme-weather-events-1.pdf

AHDB (2018) Wheat growth guide, https://cereals.ahdb.org.uk/media/185687/g66-wheat-growth-guide.pdf

Akimova, A., Núñez-Riboni, I., Kempf, A., and Taylor, M.H. (2016) Spatially-Resolved Influence of Temperature and Salinity on Stock and Recruitment Variability of Commercially Important Fishes in the North Sea. PLoS ONE, 11, e0161917, https://doi.org/10.1371/journal.pone.0161917

Allen Jr, S., Howe, A., Gallivan, T., Guo, X. & DeBrosse, G. 1999, "Genotype and environmental variation in reversion of triploid Crassostrea gigas to the heteroploid mosaic state", *J.Shellfish Res,* vol. 18, no. 1, pp. 293.

Allen, C.D., Breshears, D.D., McDowell, N.G., 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere 6, 1–55. doi:10.1890/ES15-00203.1

Andersen, T.; Carstensen, J.; Hernández-García, E. and Duarte, C. M. (2009): Ecological thresholds and regime shifts: approaches to identification. Trends in Ecology & Evolution 24: 49-57.

Ashby, M. and Heinemeyer, A., (2019). Prescribed burning impacts on ecosystem services in the British uplands: a methodological critique of the EMBER project. Journal of Applied Ecology.

Baier, P., Pennerstorfer, J., Schopf, A., 2007. PHENIPS — A comprehensive phenology model of Ips typographus ( L .) ( Col ., Scolytinae ) as a tool for hazard rating of bark beetle infestation 249, 171–186. doi:10.1016/j.foreco.2007.05.020

Baird, A.J., Evans, C.D., Mills, R., Morris, P.J., Page, S.E., Peacock, M., Reed, M., Robroek, B.J.M., Stoneman, R., Swindles, G.T. and Thom, T., 2019. Validity of managing peatlands with fire. Nature Geoscience, 12(11), pp.884-885.

BBC (2018a) Gove promises help for drought-hit farmers, https://www.bbc.co.uk/news/business-45018746

BBC (2018b) UK heatwave: Welsh farmers 'fighting to survive', https://www.bbc.co.uk/news/uk-wales-44704958

Beaugrand, G., Edwards, M., Brander, K., Luczak, C., & Ibanez, F. (2008). Causes and projections of abrupt climate-driven ecosystem shifts in the North Atlantic. *Ecology Letters, 11*, 1157-1168.

BEIS (2017) Sub-national electricity consumption statistics 2017. https://www.gov.uk/government/statistical-data-sets/regional-and-local-authority-electricity-consumption-statistics

Benton, T., Fairweather, D., Graves, A., Harris, J., Jones, A., Lenton, T., Norman, R., O'Riordan, T., Pope, E. and Tiffin, R., 2017. Environmental tipping points and food system dynamics: main report.

Bentz, B., Mountain, R., 2016. Modeling Bark Beetle Responses to Climate Change. doi:10.1016/B978-0-12-417156-5.00013-7

Bigler, C., Bräker, O.U., Bugmann, H., Dobbertin, M., Rigling, A., 2006. Drought as an inciting mortality factor in scots pine stands of the Valais, Switzerland. Ecosystems 9, 330–343. doi:10.1007/s10021-005-0126-2

Bigler, C., Gavin, D.G., Gunning, C., Veblen, T.T., 2007. Drought induces lagged tree mortality in a subalpine forest in the Rocky Mountains. Oikos 116, 1983–1994. doi:10.1111/j.2007.0030-1299.16034.x

Boonkum and Duangjinda (2014) Estimation of genetic parameters for heat stress, including dominance gene effects, on milk yield in Thai Holstein dairy cattle. Animal Science, 86(3). https://doi.org/10.1111/asj.12276

Bowes, M. J. *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, 1489-1999.

Bragazza, L., 2008. A climatic threshold triggers the die-off of peat mosses during an extreme heat wave. Global Change Biology, 14(11), pp.2688-2695.

Bragazza, L., Buttler, A., Robroek, B.J., Albrecht, R., Zaccone, C., Jassey, V.E. and Signarbieux, C., 2016. Persistent high temperature and low precipitation reduce peat carbon accumulation. Global change biology, 22(12), pp.4114-4123.

Brouns, K., Verhoeven, J.T. and Hefting, M.M., 2014. Short period of oxygenation releases latch on peat decomposition. Science of the Total Environment, 481, pp.61-68.

Brown LE, Holden J, Palmer SM (2014). Effects of moorland burning on the ecohydrology of river basins. Key Findings from the EMBER project. University of Leeds, UK

Brown, I., Thompson, D., Bardgett, R., Berry, P., Crute, I., Morison, J., . . . and Topp, K. (2016). UK Climate Change Risk Assessment Evidence Report: Chapter 3, Natural Environment and Natural Assets. London: Adaptation Sub-Committee of the Committee on Climate Change.

Brown, J.R. & Hartwick, E.B. 1988, "Influences of temperature, salinity and available food upon suspended culture of the Pacific oyster, Crassostrea gigas: II. Condition index and survival", *Aquaculture,* vol. 70, no. 3, pp. 253-267.

Brown, N., Jeger, M., Kirk, S., Xu, X., Denman, S., 2016. Spatial and temporal patterns in symptom expression within eight woodlands affected by Acute Oak Decline. Forest Ecology and

Management 360, 97–109. doi:10.1016/j.foreco.2015.10.026

Bruel, R. *et al.* (2018). Seeking alternative stable states in a deep lake. *Freshwater Biology*, 63, 553-568.

Bruno, John F., Bates, Amanda E., Cacciapaglia, Chris, Pike, Elizabeth P., Amstrup, Steven C., van Hooidonk, Ruben, Henson, Stephanie A. and Aronson, Richard B. (2018) Climate change threatens the world's marine protected areas Nature Climate Change pp 499-503, Vol 8, Issue 6

Caminade, C., Dijk, J. v., Baylis, M., & Williams, D. (2015). Modelling recent and future climatic suitability for fasciolosis in Europe. Geospatial Health, 301-308.

Cannon CH, Petit RJ. 2019. The oak syngameon: more than the sum of its parts. New Phytologist. doi:10.1111/nph.16091

Carroll, M., Heinemeyer, A., Pearce-Higgins, J. et al. (2015). Hydrologically driven ecosystem processes determine the distribution and persistence of ecosystem-specialist predators under climate change. Nat Commun 6, 7851 (2015) doi:10.1038/ncomms8851

Carvalho L, McDonald C, de Hoyos C, Mischke U, Phillips G, Borics G, Poikane S., Skjelbred B, Lyche Solheim A, Van Wichelen J. & Cardoso A.C., 2013. Sustaining recreational quality of European lakes: minimising the health risks from algal blooms through phosphorus control. Journal of Applied Ecology, 50, 315-323.

Carvalho L, Miller CA, Scott EM, Codd GA, Davies PS and Tyler AN, 2011. Cyanobacterial blooms: Statistical models describing risk factors for national-scale lake assessment and lake management. Science of the Total Environment, 409: 5353–5358.

Carvalho L, Stephen Thackeray, Rita Adrian, Meryem Beklioglu, Seyda Erdogan, Marko Järvinen, Stephen Maberly, Jannicke Moe, Peeter Nõges, Tiina Nõges, Jessica Richardson, Tom Shatwell, Helen Woods. EU MARS Project Deliverable 5.1: Section D5.1-4: Effects of multiple stressors on ecosystem structure and services of phytoplankton and macrophytes in European lakes, Jan 2013. http://www.mars-project.eu/files/download/deliverables/MARS_D5.1_five_reports_on_stressor_classification_and_effects_at_the_european_scale.pdf

Carvalho, L., Miller, C., Spears, B.M., Gunn, I.D.M., Bennion, H., Kirika, A. and May, L., 2012. Water quality of Loch Leven: responses to enrichment, restoration and climate change. *Hydrobiologia*, 681, 35-47.

CCC, Committee on Climate Change, (2018). Managing the coast in a changing climate, https://www.theccc.org.uk/wp-content/uploads/2018/10/Managing-the-coast-in-a-changing-climate-October-2018.pdf

CCC, Committee on Climate Change, (2019). Progress in preparing for climate change - 2019 Progress Report to Parliament, https://www.theccc.org.uk/publication/progress-in-preparing-for-climate-change-2019-progress-report-to-parliament/

CCC, Committee on Climate Change, (2020) Land use: Policies for a Net Zero UK, https://www.theccc.org.uk/publication/land-use-policies-for-a-net-zero-uk/

Chambers, F.M., Mauquoy, D., Gent, A., Pearson, F., Daniell, J.R. and Jones, P.S., 2007. Palaeoecology of degraded blanket mire in South Wales: data to inform conservation management. Biological conservation, 137(2), pp.197-209.

Charlton, M.B., Bowes, M.J., Hutchins, M.G., Orr, H.G., Soley, R. and Davison, P., 2018. Mapping eutrophication risk from climate change: future phosphorus concentrations in English rivers. Science of the Total Environment, 613, pp.1510-1526.

Chira, D., Teodorescu, R., Mantale, C., Chira, F., Isaia, G., Achim, G., Scutelnicu, A. and Botu, M. (2018). Testing chestnut hybrids for resistance to Cryphonectria parasitica. Acta Hortic. 1220, 113-120. DOI: 10.17660/ActaHortic.2018.1220.17

Clark JM, Gallego-Sala AV, Allott TE, Chapman SJ, Farewell T, Freeman C, House JI, Orr HG, Prentice IC, Smith P (2010). Assessing the vulnerability of blanket peat to climate change using an ensemble of statistical bioclimatic envelope models. Climate Research, 45, 131-150.

Clark, R. A., Fox, C. J., Viner, D., and Livermore, M. 2003. North Sea cod and climate change -modelling the effects of temperature on population dynamics. Global Change Biology, 9: 1-12.

Clarke, J., Bailey, D., and Wright, P. 2015. Evaluating the effectiveness of a seasonal spawning area closure. ICES Journal of Marine Science.

Codd et al. 2005. Toxicology and Applied Pharmacology 203: 264-272.

Coll J, Bourke D, Skeffington MS, Gormally M, Sweeney J. (2014). Projected loss of climate space for active blanket bog in Ireland. In In the bog: the ecology, landscape, archaeology and heritage of peatlands conference, Sheffield, UK, 3-5.

Colosimo, A., Giuliani, A., Maranghi, F., Brix, O.,Thorkildsen, S., Fischer, T., Knust, R. & Poertner, H. O. 2003 Physiological and genetical adaptation to temperature in fish populations. Continental Shelf Research 23, 1919–1928. (doi:10.1016/j.csr.2003.06.012)

Convery, F.J. and Wagner, G., 2015. Reflections–managing uncertain climates: some guidance for policy makers and researchers. Review of Environmental Economics and Policy, 9(2), pp.304-320.

Damos, P., Savopoulou-soultani, M., 2012. Temperature-Driven Models for Insect Development and Vital Thermal Requirements 2012. doi:10.1155/2012/123405

Dantec, C.F., Ducasse, H., Capdevielle, X., Fabreguettes, O., Delzon, S., Desprez-Loustau, M.L., 2015. Escape of spring frost and disease through phenological variations in oak populations along elevation gradients. Journal of Ecology 103, 1044–1056. doi:10.1111/1365-2745.12403

Davies GM, Kettridge N, Stoof CR, Gray A, Ascoli D, Fernandes PM, Marrs R, Allen KA, Doerr SH, Clay GD, McMorrow J (2016). The role of fire in UK peatland and moorland management: the need for informed, unbiased debate. Philosophical Transactions of the Royal Society B: Biological Sciences, 371, 20150342.

Davies, O. and Kerr, G., 2011. The costs and revenues of transformation to continuous cover forestry. Report to the Forestry Commission by Forest Research.

Defra (2018) Sustainable fisheries for future generations, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/722074/fisheries-wp-consult-document.pdf

Denman, S., Brown, N., Kirk, S., Jeger, M., Webber, J., 2014. A description of the symptoms of Acute Oak Decline in Britain and a comparative review on causes of similar disorders on oak in Europe. Forestry 87, 535–551. doi:10.1093/forestry/cpu010

Diaz, D. and Keller, K., 2016. A potential disintegration of the West Antarctic Ice Sheet: implications for economic analyses of climate policy. American Economic Review, 106(5), pp.607-11.

Dieleman, C. M., Branfireun, B. A., McLaughlin, J. W., & Lindo, Z. (2014). Climate change drives a shift in peatland ecosystem plant community: Implications for ecosystem function and stability. Global Change Biology, 21(1), 388-395.

Dodds, W. (2017). Flood and Coastal Erosion Risk Management in Wales. Report to the national Assembly for Wales; paper number 17-024.

Dolschak K, Gartner K, Berger TW. 2019. The impact of rising temperatures on water balance and phenology of European beech (Fagus sylvatica L.) stands. Model Earth Syst Environ 5(4): 1347-1363.

Drinkwater, K.F., 2005. The response of Atlantic cod (Gadus morhua) to future climate change. ICES Journal of Marine Science, 62(7), pp.1327-1337.

Drobyshev, I., Niclasson, M., Eggertsson, O., Linderson, H., Sonesson, K., 2008. Original article Influence of annual weather on growth of pedunculate oak in southern Sweden. Annals of Forest Science 65, 512–524.

Dubois S, Commito JA, Olivier F, Retiere C (2006) Effects of epibionts on Sabellaria alveolata (L.) biogenic reefs and their associated fauna in the Bay of Mont Saint-Michel. Estuarine Coastal and Shelf Science 68:635-646

Dutil, J-D., and Brander, K. 2003. Comparing productivity of North Atlantic cod (Gadus morhua) stocks and limits to growth production. Fisheries Oceanography, 12: 502-512.

Edwards, T. (2017). *Future of the Sea: Current and Future Impacts of Sea Level Rise on the UK.* Foresight, Government Office for Science.

Elliott J. A. (2010). The seasonal sensitivity of Cyanobacteria and other phytoplankton to changes in flushing rate and water temperature. *Global Change Biology*, 16, 864-876.

Elliott, J. A. & Bell, V. A. (2011). Predicting the potential long-term influence of climate change on vendace (*Coregonus albula*) habitat in Bassenthwaite Lake, UK. *Freshwater Biology*, 56, 395-405.

Elliott, J.A. (2012). Is the future blue-green? A review of the current model predictions of how climate change could affect pelagic freshwater cyanobacteria. *Water Research*, 46, 1364-1371.

Elliott, J.A., Henrys, P., Tanguy, M., Cooper, J. and Maberly, S.C., 2015. Predicting the habitat expansion of the invasive roach Rutilus rutilus (Actinopterygii, Cyprinidae), in Great Britain. Hydrobiologia, 751(1), pp.127-134.

Elliott, M. Holden, J. (2018) UK sea fisheries statistics 2017. Marine Management Organisation, pp 174.

Engelhard, G.H., Righton, D.A. and Pinnegar, J.K., 2014. Climate change and fishing: a century of shifting distribution in North Sea cod. Global change biology, 20(8), pp.2473-2483.

Escapa M, Isacch JP, Daleo P, Alberti J, Iribarne O, Borges M, Dos Santos EP, Gagliardini DA, Lasta M (2004) The distribution and ecological effects of the introduced Pacific oyster Crassostrea gigas (Thunberg, 1793) in northern Patagonia. Journal of Shellfish Research 23:765-772

Estop-Aragonés, C. and Blodau, C., 2012. Effects of experimental drying intensity and duration on respiration and methane production recovery in fen peat incubations. Soil Biology and Biochemistry, 47, pp.1-9.

Evans C, Artz R, Moxley J, Smyth M-A, Taylor E, Archer N, Burden A, Williamson J, Donnelly D, Thomson A, Buys G, Malcolm H, Wilson D, Renou-Wilson F. (2017). Implementation of an emission inventory for UK peatlands. Report to the Department for Business, Energy and Industrial Strategy, Centre for Ecology and Hydrology, Bangor. 88pp.

Evans, C.D., Bonn, A., Holden, J., Reed, M.S., Evans, M.G., Worrall, F., Couwenberg, J. and Parnell, M., 2014. Relationships between anthropogenic pressures and ecosystem functions in UK blanket bogs: Linking process understanding to ecosystem service valuation. Ecosystem Services, 9, pp.5-19.

FAO. 2013, Climate Smart Agriculture Sourcebook, 570 pp., FAO, Rome http://www.fao.org/3/a-i4373e.pdf

Favis-Mortlock, D., & Boardman, J. (1995). Nonlinear responses of soil erosion to climate change: a modelling study on the UK South Downs. Catena, 25, 365-387.

Fenner N, Freeman C (2011). Drought-induced carbon loss in peatlands. Nature Geoscience, 4, 895.

Fernandes, J.A., Papathanasopoulou, E., Hattam, C., Queirós, A.M., Cheung, W.W., Yool, A., Artioli, Y., Pope, E.C., Flynn, K.J., Merino, G. and Calosi, P., 2017. Estimating the ecological, economic and social impacts of ocean acidification and warming on UK fisheries. *Fish and Fisheries*, *18*(3), pp.389-411.

Ferretto A, Brooker R, Aitkenhead M, Matthews R, Smith P (2019). Potential carbon loss from Scottish peatlands under climate change. Regional Environmental Change, 19, 2101-2111.

Fey F, Dankers N, Steenbergen J, Goudswaard K (2010). Development and distribution of the non-indigenous Pacific oyster (Crassostrea gigas) in the Dutch Wadden Sea. Aquaculture International 18:45-59

Field E, Schönrogge K, Barsoum N, Hector A, Gibbs M. 2019. Individual tree traits shape insect and disease damage on oak in a climate-matching tree diversity experiment. Ecology and Evolution 9: 8524– 8540.

Field E, Schönrogge K, Barsoum N, Hector A, Gibbs M. 2019. Individual tree traits shape insect and disease damage on oak in a climate-matching tree diversity experiment. Ecology and Evolution 9: 8524– 8540.

Field, E.; Castagneyrol, B.; Gibbs, M.; Jactel, H.; Barsoum, N.; Schonrogge, K.; Hector, A. (in press). Tree trait, insect herbivore abundance and powdery mildew infection data from a tree diversity experiment in south-west France

Ford, K.R., Breckheimer, I.K., Franklin, J.F., Freund, J.A., Kroiss, S.J., Larson, A.J., Theobald, E.J., Hillerislambers, J., Sarg, R., Franco, M., 2017. Competition alters tree growth responses to climate at individual and stand scales 62, 53–62.

Fox, N. J., Marion, G., Davidson, R. S., White, P. C., & Hutchings, M. R. (2015). Climate-driven tipping-points could lead to sudden, high-intensity parasite outbreaks. Royal Society Open Science, 2, 1-14.

Freeman C, Ostle N, Kang H (2001). An enzymic 'latch' on a global carbon store. Nature, 409, 149.

Gallego-Sala AV, Clark JM, House JI, Orr HG, Prentice IC, Smith P, Farewell T, Chapman SJ (2010). Bioclimatic envelope model of climate change impacts on blanket peatland distribution in Great Britain. Climate Research, 45, 151-162.

Gallego-Sala AV, Prentice IC (2013). Blanket peat biome endangered by climate change. Nature Climate Change. 2013, 152.

Garnett MH, Ineson P, Stevenson AC (2000). Effects of burning and grazing on carbon sequestration in a Pennine blanket bog, UK. The Holocene, 10, 729-36.

Gibbs M.M., Howard-Williams C. (2018) Physical Processes for In-Lake Restoration: Destratification and Mixing. In: Hamilton D., Collier K., Quinn J., Howard-Williams C. (eds) Lake Restoration Handbook. Springer, Cham.

Gibbs, J.N., Greig, B.J.W., 1997. Biotic and abiotic factors affecting the dying back of peduculate oak (Quercus robur L). Forestry 70, 399–406.

Glenk K, Martin-Ortega J (2018). The economics of peatland restoration. Journal of Environmental Economics and Policy, 7, 345-62.

Gobler, C.J., Doherty, O.M., Hattenrath-Lehmann, T.K., Griffith, A.W., Kang, Y. and Litaker, R.W., 2017. Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. *Proceedings of the National Academy of Sciences*, *114*(19), pp.4975-4980.

Gonzalez-Irusta, J. and Wright, P.J. (2016) Spawning grounds of Atlantic cod (Gadus morhua) in the North Sea. ICES Journal of Marine Science, 73, 304–315.

Graves, A., Morris, J., Deeks, L.K., Rickson, J., Kibblewhite, M.G., Harris, J.A., Farewell, T.S., 2011. The Total Costs of Soils Degradation in England and Wales. Defra project CTE0946: Final Report submitted to Defra, Cranfield University, Bedford (184 pp.).

Graves, A.R., Morris, J., Deeks, L.K., Rickson, R.J., Kibblewhite, M.G., Harris, J.A., Farewell, T.S. and Truckle, I., 2015. The total costs of soil degradation in England and Wales. Ecological Economics, 119, pp.399-413.

Green, S., Hendry, S.J., Redfern, D.B., 2008. Drought damage to pole-stage Sitka spruce and other conifers in north-east Scotland. Scottish Forestry 62(2) 62, 10–18.

Green, S., Ray, D., 2009. Potential impacts of drought and disease on forestry in Scotland. Forest Research 8.

Guy, C. & Roberts, D. 2010, "Can the spread of non-native oysters (Crassostrea gigas) at the early stages of population expansion be managed?", *Marine pollution bulletin,* vol. 60, no. 7, pp. 1059-1064.

Gyllström *et al* (2005). The role of climate in shaping zooplankton communities of shallow lakes. *Limnology & Oceanography*, 50, 2008-2021.

Hacket-pain, A., Cavin, L., Friend, A., Jump, A.S., 2016. Consistent limitation of growth by high temperature and low precipitation from range core to southern edge of European beech indicates widespread vulnerability to changing climate : Consistent limitation of growth by high temperature and low precipitation from range core to southern edge of European beech indicates widespread vulnerability to changing climate. doi:10.1007/s10342-016-0982-7

Hacket-Pain, A., Cavin, L., Friend, A., Jump, A.S., 2016. Consistent limitation of growth by high temperature and low precipitation from range core to southern edge of European beech indicates widespread vulnerability to changing climate. European Journal of Forest Research 135:897-909

Hansom, J.D., Fitton, J.M., and Rennie, A.F. (2017) Dynamic Coast - National Coastal Change Assessment: National Overview, CRW2014/2.

Harrison, P., Sier, A., Acreman, M., Bealey, B., Fry, M., Jones, L., Maskell, L., May, L., Norton, L., Read, D., Reis, S., Trembath, P., Watkins, J. (2017). Natural Capital Metrics. Phase 1 Final Report: Central components. CEH Project NEC06063. May 2017.

Harrower CA, Scalera R, Pagad S, Schonrogge K, Roy HE (2018) Guidance for interpretation of CBD categories on introduction pathways. Report to the European Commission. https://circabc.europa.eu/w/browse/0606f9b8-b567-4f53-9bc8-76e7800f0971. Accessed 4 Sept 2018

Hendriks, I.E., Duarte, C.M. and Álvarez, M., 2010. Vulnerability of marine biodiversity to ocean acidification: a meta-analysis. *Estuarine, Coastal and Shelf Science*, *86*(2), pp.157-164.

Henman, J., & Poulter, B. (2008). Inundation of freshwater peatlands by sea level rise: Uncertainty and potential carbon cycle feedbacks. Journal of Geophysical Research: Biogeosciences ,113 (1), 1-11.

Herbert R.J.H., Roberts C., Humphreys J., and Fletcher S (2012) The Pacific Oyster (Crassostrea gigas) in the UK: Economic, Legal and Environmental Issues Associated with its Cultivation, Wild Establishment and Exploitation. Report for the Shellfish Association of Great Britain. http://www.shellfish.org.uk/files/PDF/73434Pacific%20Oysters%20Issue%20Paper_final_241012.pdf

Herbert, R.J., 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 and Conservation,* vol. 25, no. 14, pp. 2835-2865.

Hermans, T. H. J., Tinker, J., Palmer, M. D., Katsman, C. A., Vermeersen, B. L. A., Slangen, A. B. A., (2019). Improving sea-level projections on the North western European shelf using dynamical downscaling. Climate Dynamics, https://doi.org/10.1007/s00382-019-05104-5.

Hinrichsen, H.-H., Huwer, B., Makarchouk, A., Petereit, C., Schaber, M., & Voss, R. (2011). Climate-driven long-term trends in Baltic Sea oxygen concentrations and the potential consequences for eastern Baltic cod (Gadus morhua). *Journal of Marine Science, 68 (10)*, 2019-2028.

HM Government (2018) A Green Future: Our 25 Year Plan to Improve the Environment, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf

Ho, J.C., Michalak, A.M. and Pahlevan, N., 2019. Widespread global increase in intense lake phytoplankton blooms since the 1980s. Nature, 574(7780), pp.667-670.

Holden, J., Chapman, P.J., Palmer, S.M., Kay, P. and Grayson, R., 2012b. The impacts of prescribed moorland burning on water colour and dissolved organic carbon: a critical synthesis. Journal of environmental management, 101, pp.92-103.

Holden, J., Smart, R.P., Dinsmore, K.J., Baird, A.J., Billett, M.F. and Chapman, P.J., 2012a. Natural pipes in blanket peatlands: major point sources for the release of carbon to the aquatic system. Global Change Biology, 18(12), pp.3568-3580.

Huebert, K.B., Pätsch, J., Hufnagl, M., Kreus, M. and Peck, M.A. (2018) Modeled larval fish prey fields and growth rates help predict recruitment success of cod and anchovy in the North Sea. Marine Ecology Progress Series, 600, 111–126.

Hughes PD, Lomas-Clarke SH, Schulz J, Jones P (2007). The declining quality of late-Holocene ombrotrophic communities and the loss of *Sphagnum austinii* (Sull. ex Aust.) on raised bogs in Wales. The Holocene, 17, 613-25.

Huisman, J., Codd, G.A., Paerl, H.W., Ibelings, B.W., Verspagen, J.M. and Visser, P.M., 2018. Cyanobacterial blooms. *Nature Reviews Microbiology*, *16*(8), p.471.

Ibelings, B.W., Portielje, R., Lammens, E.H., Noordhuis, R., van den Berg, M.S., Joosse, W. and Meijer, M.L., 2007. Resilience of alternative stable states during the recovery of shallow lakes from eutrophication: Lake Veluwe as a case study. Ecosystems, 10(1), pp.4-16.

Jacobs. (2018). Research to Assess the Economics of Coastal Change Management in England and to Determine Potential Pathways for a Sample of Exposed Communities. Report to Committee on Climate Change

Jactel H, Petit J, Desprez-Loustau M-L, Delzon S, Piou D, Battisti A, Koricheva J. 2012. Drought effects on damage by forest insects and pathogens: a meta-analysis. Global Change Biology 18(1): 267-276.

Jactel H., Koricheva, J., Castagneyrol, B. (2019) Responses of forest insect pests to climate change: not so simple, Current Opinion in Insect Science, 35, 103-108. DOI: https://doi.org/10.1016/j.cois.2019.07.010

Jactel, H., Bauhus, J., Boberg, J., Bonal, D., Castagneyrol, B., Gardiner, B., Gonzalez-Olabarria, J.R., Koricheva, J., Meurisse, N., Brockerhoff, E.G., 2017. Tree Diversity Drives Forest Stand Resistance to Natural Disturbances. Current Forestry Reports 3, 223–243. doi:10.1007/s40725-017-0064-1

Jactel, H., Branco, M., Duncker, P., Gardiner, B., Grodzki, W., Langstrom, B., 2012. A Multicriteria Risk Analysis to Evaluate Impacts of Forest Management Alternatives on Forest Health in Europe 17.

Jassey, V. E., Reczuga, M. K., Zielińska, M., Słowińska, S., Robroek, B. J., Mariotte, P., . . . al., e. (2017). Tipping point in plant–fungal interactions under severe drought causes abrupt rise in peatland ecosystem respiration. Global Change Biology, 24(3), 972-986.

Jöhnk, K. D., Huisman, J., Sharples, J., Sommeijer, B., Visser, P. M. & Stroom. J. M. (2008). Summer heatwaves promote blooms of harmful cyanobacteria. *Global Change Biology*, 14, 495-512.

Johnson, H., Kovats, R.S., McGregor, G., Stedman, J., Gibbs, M., Walton, H., Cook, L. and Black, E., 2005. The impact of the 2003 heat wave on mortality and hospital admissions in England. Health Statistics Quarterly, (25), pp.6-11.

Jones M.L.M., Angus S., Cooper A., Doody P., Everard M., Garbutt A., Gilchrist P., Hansom G., Nicholls R., Pye K., Ravenscroft N., Rees S., Rhind P. & Whitehouse A. (2011) Coastal margins [chapter 11]. In: UK National Ecosystem Assessment. Understanding nature's value to society. Technical Report. Cambridge, UNEP-WCMC, 411-457.

Jones, A., Stolbovoy, V., Rusco, E., Gentile, A.-R., Gardi, C., Marechal, B., & Montanarella, L. (2009). Climate Change in Europe. 2. Impact on soil. A review . Agronomy for Sustainable Development, 29(3), 423- 432.

Jucker, T., Bouriaud, O., Avacaritei, D., Iulian, D., Duduman, G., Valladares, F., Coomes, D.A., 2014. Competition for light and water play contrasting roles in driving diversity – productivity relationships in Iberian forests. Journal of Ecology102 1202–1213. doi:10.1111/1365-2745.12276

Kantamaneni, K. (2016). Counting the cost of coastal vulnerability. *Ocean & Coastal Management, 132*, 155-169.

Kerr, G., Haufe, J., January, V., 2011. Thinning Practice A Silvicultural Guide By 1–54.

King, M.G. 1977, "Cultivation of the Pacific oyster (Crassostrea gigas) in a non-tidal hypersaline pond", *Aquaculture,* vol. 11, no. 2, pp. 123-136.

Kochmann J, Buschbaum C, Volkenborn N, Reise K (2008) Shift from native mussels to alien oysters: Differential effects of ecosystem engineers. Journal of Experimental Marine Biology and Ecology 364:1-10

Kroeker, K.J., Kordas, R.L., Crim, R.N. and Singh, G.G., 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecology letters*, *13*(11), pp.1419-1434.

Kubiak K, Żółciak A, Damszel M, Lech P, Sierota Z. 2017. Armillaria Pathogenesis under Climate Changes. Forests 8(4): 100.

Lallias, D., Boudry, P., Batista, F.M., Beaumont, A., King, J.W., Turner, J.R. & Lapègue, S. 2015, "Invasion genetics of the Pacific oyster Crassostrea gigas in the British Isles inferred from microsatellite and mitochondrial markers", *Biological Invasions,* vol. 17, no. 9, pp. 2581-2595.

Lindsay, R. (2010). Peatbogs and carbon: a critical synthesis to inform policy development in oceanic peat bog conservation and restoration in the context of climate change. RSPB, 315 pp.

Lowe, J.A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Eagle, K., Edwards, T., Fosser, G. and Fung, F., 2018. UKCP18 science overview report. Met Office Hadley Centre: Exeter, UK.

Lund, M., Christensen, T. R., Lindroth, A., & Schubert, P. (2012). Effects of drought conditions on the carbon dioxide dynamics in a temperate peatland. Environmental Research Letters, 7, 1-7.

Lürling, M., Mackay, E., Reitzel, K., & Spears, B. M. (2016). A critical perspective on geo-engineering for eutrophication management in lakes. Water Research, 97, 1-10.

Mann, R. 1979, "Some biochemical and physiological aspects of growth and gametogenesis in Crassostrea gigas and Ostrea edulis grown at sustained elevated temperatures", *Journal of the Marine Biological Association of the United Kingdom,* vol. 59, no. 1, pp. 95-110.

Mantzouki, E., Visser, P.M., Bormans, M. et al. Aquat Ecol (2016) 50: 333.

Markert, A., Esser, W., Frank, D., Wehrmann, A. & Exo, K. 2013, "Habitat change by the formation of alien Crassostrea-reefs in the Wadden Sea and its role as feeding sites for waterbirds", *Estuarine, Coastal and Shelf Science,* vol. 131, pp. 41-51.

Marrs RH, Marsland EL, Lingard R, Appleby PG, Piliposyan GT, Rose RJ, O'Reilly J, Milligan G, Allen KA, Alday JG, Santana V (2019). Experimental evidence for sustained carbon sequestration in fire-managed, peat moorlands. Nature Geoscience, 12, 108.

Martinez-Vilalta J, Poyatos R, Aguade D, Retana J, Mencuccini M. 2014. A new look at water transport regulation in plants. New Phytol 204(1): 105-115.

Martin-Ortega J, Allott TE, Glenk K, Schaafsma M (2014). Valuing water quality improvements from peatland restoration: Evidence and challenges. Ecosystem Services, 9, 34-43.

Maskill, R., Sunter, K., Buckler, M., Wittram, B., King. L and Walker, J.S. (2015) MoorLIFE: A carbon audit of the project: Final report

Mason, W.L., Connolly, T., 2020. What influences the long-term development of mixtures in British forests? Forestry doi:10.109, 1–12. doi:10.1093/forestry/cpaa003

May, L., Taylor, P., Spears, B., Pitt, J.A., Collins, A.L., Corkley, I., Anthony, S., Skirvin, D., Lee, D. and Naden, P., 2019. Decision support framework to identify lakes that are likely to meet water quality targets if external inputs of phosphorus from agriculture are reduced. Limnetica, 38(1), pp.489-501.

MCCIP (2017). Marine Climate Change impacts: 10 years' experience of science to policy reporting. (Eds. Frost M., Baxter J. Buckley P., Dye S. and Stoker B.). Summary Report, MCCIP, Lowestoft, 12pp. doi:10.14465/2017.arc10.000-arc. 10 year MCCIP Report Card 2017.

McKnight, W. & Chudleigh, I.J. 2015, "Pacific oyster Crassostrea gigas control within the inter-tidal zone of the North East Kent Marine Protected Areas, UK", *Conservation Evidence,* vol. 12, pp. 28-32.

Met Office Hadley Centre (2018): UKCP18 Global Projections by Administrative Regions over the UK for 1900-2100. Centre for Environmental Data Analysis, date of citation. https://catalogue.ceda.ac.uk/uuid/7ebab0df1a794d1fae245256af7de633

Met Office Hadley Centre (2018): UKCP18 Regional Projections by Administrative Regions over the UK for 1980-2080. Centre for Environmental Data Analysis, 18/01/2019.

Mitchell, R.J., Bellamy, P.E., Ellis, C.J., Hewison, R.L., Hodgetts, N.G., Iason, G.R., Littlewood, N.A., Newey, S., Stockan, J.A., Taylor, A.F.S., 2019. Collapsing foundations : The ecology of the British oak , implications of its decline and mitigation options. Biological Conservation 0–1. doi:10.1016/j.biocon.2019.03.040

Morecroft, M.D., Taylor, M.E., Oliver, H.R., 1998. Air and soil microclimates of deciduous woodland compared to an open site.

Mountford, E.P., Peterken, G.F., 2003. Long-term change and implications for the management of wood- pastures : experience over 40 years from Denny Wood New Forest. Forestry 76.

Mullan, D., Favis-Mortlock, D., & Fealy, R. (2012). Addressing key limitations associated with modelling soil erosion under the impacts of future climate change. Agricultural and Forest Meteorology, 156, 18-30.

Neat, F. and Righton, D. (2007) Warm water occupancy by North Sea cod. Proceedings of the Royal Society B: Biological Sciences, 274, 789–798.

Neat, F., Bendall, V., Berx, B., Wright, P., Cuaig, M.Ó., Townhill, C., Schön, P.-J., Lee, J. and Righton, D.A. (2014) Movement of Atlantic cod around the British Isles. Journal of Applied Ecology, 51, 1564–1574.

Nell, J.A. 2002, "Farming triploid oysters", *Aquaculture,* vol. 210, no. 1-4, pp. 69-88.

NFI (2013) Standing volume of broadleaves in woodland in Great Britain, Forestry Commission, Edinburgh

Nicolas, D., Rochette, S., Llope, M. and Licandro, P. (2014) Spatio-temporal variability of the North Sea cod recruitment in relation to temperature and zooplankton. PLoS ONE, 9, e88447.

Núñez-Riboni, I., Taylor, M.H., Kempf, A., Püts, M. and Mathis, M., 2019. Spatially resolved past and projected changes of the suitable thermal habitat of North Sea cod (Gadus morhua) under climate change. ICES Journal of Marine Science, 76(7), pp.2389-2403.

O'Brien, C.M., Fox, C.J., Planque, B., Casey, J. (2000) Climate variability and North Sea cod. Nature, 404, 142, doi:10.1038/35004654

Oosterbaan, A., Nabuurs, G.J., 1991. Relationships between oak decline and groundwater class in The Netherlands. Plant and Soil 136, 87–93. doi:10.1007/BF02465223

Paerl, H. W. & Huisman, J. (2008). Blooms like it hot. *Science*, 320, 57-58.

Palmer, M.D., Howard, T., Tinker, J., Lowe, J.A., Bricheno, L., Calvert, D., Edwards, T., Gregory, J., Harris, G., Krijnen, J. Pickering, M., Roberts, C., Wolf, J. 2018. UKCP18 Marine report. Exeter: Met

Office. November 2018. https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Marine-report.pdf

Paul Watkiss Associates (2019) Impacts of climate change on meeting Government outcomes in England (Paul Watkiss Associates), https://www.theccc.org.uk/publication/impacts-of-climate-change-on-meeting-government-outcomes-in-england-paul-watkiss-associates/

Pearce-Higgins, J.W. and Yalden, D.W., 2004. Habitat selection, diet, arthropod availability and growth of a moorland wader: the ecology of European Golden Plover Pluvialis apricaria chicks. Ibis, 146(2), pp.335-346.

Peterken, G.F., Mountford, E.P., 1996. Effects of drought on beech in Lady Park Wood, an unmanaged mixed deciduous woodland 69.

Petr, M., Boerboom, L.G.J., van der Veen, A., Ray, D., 2014. A spatial and temporal drought risk assessment of three major tree species in Britain using probabilistic climate change projections. Climatic Change 124, 791–803. doi:10.1007/s10584-014-1122-3

Phillips, G., Bennion, H., Perrow, M.R., Sayer, C.D., Spears, B.M., Willby, N. (2015) A review of lake restoration practices and their performance in the Broads National Park, 1980-2013. Report for Broads Authority, Norwich and Natural England.

POST (The Parliamentary Office of Science and Technology) (2015). Securing UK Soil Health. PostNote Number 502 August 2015.

Pretty, J.N., Mason, C.F., Nedwell, D.B., Hine, R.E., Leaf, S. and Dils, R., 2003. Environmental costs of freshwater eutrophication in England and Wales. Environmental Science and Technology. 37(2)

Price, A.J.E., 2015. Shake in oak : an evidence review. Forestry Commission Research Report. Edinburgh.

Pyatt, D.G., Ray, D., Fletcher, J., 2001. An Ecological Site Classification for Forestry in Great Britain, FC Bulleti. ed. Forestry Commission, Edinburgh.

Ramsfield, T.D., Bentz, B.J., Faccoli, M., Jactel, H., Brockerhoff, E.G., 2016. Forest health in a changing world: Effects of globalization and climate change on forest insect and pathogen impacts. Forestry 89, 245–252. doi:10.1093/forestry/cpw018

Reyer, et al. 2017. Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? Environmental Research Letters 12. doi:10.1088/1748-9326/aa5ef1

Reynolds, C.S., Huszar, V., Kruk, C., Naselli-Flores, L., Melo, S. 2002. Towards a functional classification of the freshwater phytoplankton, Journal of Plankton Research, 24(5), 417–428.

Richardson J., Miller C., Maberly S.C., Taylor P., Globevnik L., Hunter P., Jeppesen E., Mischke U., Moe J., Pasztaleniec A., Søndergaard M. and Carvalho L., 2018. Effects of multiple stressors on cyanobacteria biovolume varies with lake type. Global Change Biology, 24, 5044-5055. www.doi.org/10.1111/gcb.14396

Righton, D.A., Andersen, K.H., Neat, F., Thorsteinsson, V., Steingrund, P., Svedäng, H. et al. (2010) Thermal niche of Atlantic cod Gadus morhua: limits, tolerance and optima. Marine Ecology Progress Series, 420, 1–13.

Rigosi A, Carey CC, Ibelings BW, Brookes JD (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.

Robins, P.E., Skov, M.W., Lewis, M.J., Gimenez, L., Davies, A.G., Malham, S.K., Neill, S.P., McDonald, J.E., Whitton, T.A., Jackson, S.E. and Jago, C.F., 2016. Impact of climate change on UK estuaries: A review of past trends and potential projections. *Estuarine, Coastal and Shelf Science*, *169*, pp.119-135.

Rocha, J., Yletyinen, J., Biggs, R., Blenckner, T. and Peterson, G., 2015. Marine regime shifts: drivers and impacts on ecosystems services. Philosophical Transactions of the Royal Society B: Biological Sciences, 370(1659), p.20130273.

Roman DT, Novick KA, Brzostek ER, Dragoni D, Rahman F, Phillips RP. 2015. The role of isohydric and anisohydric species in determining ecosystem-scale response to severe drought. Oecologia 179(3): 641-654.

Roy HE, Hesketh H, Purse BV, Eilenberg J, Santini A, Scalera R, Stentiford GD, Adriaens T, Bacela-Spychalska K, Bass D, et al. 2017. Alien Pathogens on the Horizon: Opportunities for Predicting their Threat to Wildlife. Conservation Letters 10(4): 477-484.

Roy HE, Peyton J, Aldridge DC, Bantock T, Blackburn TM, Britton R, Clark P, Cook E, Dehnen-Schmutz K, Dines T, et al. 2014. Horizon scanning for invasive alien species with the potential to threaten biodiversity in Great Britain. Glob Chang Biol 20(12): 3859-3871.

Roy, H.E., Hesketh, H., Purse, B.V., Eilenberg, J., Santini, A., Scalera, R., Stentiford, G.D., Adriaens, T., Bacela-Spychalska, K., Bass, D. and Beckmann, K.M., 2017. Alien pathogens on the horizon: Opportunities for predicting their threat to wildlife. Conservation Letters, 10(4), pp.477-484.

Ruesink, J.L., Lenihan, H.S., Trimble, A.C., Heiman, K.W., Micheli, F., Byers, J.E. & Kay, M.C. 2005, "Introduction of non-native oysters: ecosystem effects and restoration implications", *Annu.Rev.Ecol.Evol.Syst.,* vol. 36, pp. 643-689.

Saenz-Romero C, Lamy JB, Ducousso A, Musch B, Ehrenmann F, Delzon S, Cavers S, Chalupka W, Dagdas S, Hansen JK, et al. 2017. Adaptive and plastic responses of Quercus petraea populations to climate across Europe. Glob Chang Biol 23(7): 2831-2847.

Salmaso, N. & Zignin, A. (2010). At the extreme of physical gradients: phytoplankton in highly flushed, large rivers. *Hydrobiologia*, 639, 21-36.

Sanseverino, I., Conduto, D., Pozzoli, L., Dobricic, S., & Lettieri, T. (2016). *Algal bloom and its economic impact.* European Comission: JRC Technical Reports.

Savill, P.S., Mather, R.A., Road, S.P., 1990. A Possible Indicator of Shake in Oak : Relationship between Flushing Dates and Vessel Sizes 63.

Sayers, P.B., Horritt, M., Penning-Rowsell, E. and McKenzie, A., (2015). Climate Change Risk Assessment 2017: Projections of future flood risk in the UK. Research undertaken by Sayers and Partners on behalf of the Committee on Climate Change. Published by Committee on Climate Change, London.

Scheffer, M. (2009): Critical transitions in nature and society, Princeton, New Jersey: Princeton University Press.

Scheffer, M., Hosper, S.H., Meijer, M.L., Moss, B. and Jeppesen, E., 1993. Alternative equilibria in shallow lakes. Trends in ecology & evolution, 8(8), pp.275-279.

Scottish Association for Marine Science (2015) Survey of Wild Pacific Oyster Crassostrea Gigas in Scotland http://www.sarf.org.uk/cms-assets/documents/207056-140687.sarf099.pdf

Scottish Government (2015) The river basin management plan for the Scotland river basin district:

2015–2027, https://www.sepa.org.uk/media/163445/the-river-basin-management-plan-for-the-scotland-river-basin-district-2015-2027.pdf

Scottish Government (2018) CLIMATE CHANGE PLAN The Third Report on Proposals and Policies 2018-2032 https://www.gov.scot/publications/scottish-governments-climate-change-plan-third-report-proposals-policies-2018/

Seedre, M., Felton, A., Lindbladh, M., 2018. What is the impact of continuous cover forestry compared to clearcut forestry on stand ‐ level biodiversity in boreal and temperate forests ? A systematic review protocol. Environmental Evidence 1–8. doi:10.1186/s13750-018-0138-y

Seidl R, Rammer W. 2017. Climate change amplifies the interactions between wind and bark beetle disturbances in forest landscapes. Landsc Ecol 32(7): 1485-1498.

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T.A., Reyer, C.P.O., 2017. Forest disturbances under climate change. Nature Climate Change 7, 395–402. doi:10.1038/nclimate3303

Sherwood JH, Kettridge N, Thompson DK, Morris PJ, Silins U, Waddington JM (2013). Effect of drainage and wildfire on peat hydrophysical properties. Hydrological Processes, 27, 1866-1874.

Short, E. E., Caminade, C., & Thomas, B. N. (2017). Climate Change Contribution to the Emergence or Re-Emergence of Parasitic Diseases. Infectious Diseases: Research and Treatment, 10, 1-7.

Shpigel, M. & Blaylock, R.A. 1991, "The Pacific oyster, Crassostrea gigas, as a biological filter for a marine fish aquaculture pond", *Aquaculture,* vol. 92, pp. 187-197.

Silva Foundation, 2017. Why manage woodland & who benefits ? Long Wittenham, UK.

Simard, F., Laffoley, D. and J.M. Baxter (editors), 2016. Marine Protected Areas and Climate Change: Adaptation and Mitigation Synergies, Opportunities and Challenges. Gland, Switzerland: IUCN. 52 pp.

Sinclair FH, Stone GN, Nicholls JA, Cavers S, Gibbs M, Butterill P, Wagner S, Ducousso A, Gerber S, Petit RJ, et al. 2015. Impacts of local adaptation of forest trees on associations with herbivorous insects: implications for adaptive forest management. Evol Appl 8(10): 972-987.

Smale, D.A., Wernberg, T., Oliver, E.C., Thomsen, M., Harvey, B.P., Straub, S.C., Burrows, M.T., Alexander, L.V., Benthuysen, J.A., Donat, M.G. and Feng, M., 2019. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nature Climate Change, 9(4), p.306.

Spears, B.M., Andrews, C., Banin, L., Carvalho, L., Cole, S., De Ville, M., Gunn, I.D.M., Ives, S., Lawlor, A., Leaf, S., Lofts, S., Maberly, S.C., Madgwick, G., May, L., Moore, A., Pitt, J., Smith, R., Waters, K., Watt, J., Winfield, I.J, Woods, H. 2018. Assessment of sediment phosphorus capping to control nutrient concentrations in English lakes. Environment Agency Report No. SC120064/R9

Spears, B.M., L. Carvalho, D.M. Paterson. 2006. Phosphorus partitioning in a shallow lake: implications for water quality management. Water and Environment Journal. 21, 47-53.

Spears, B.M., May, L. 2015. Long-term homeostasis of filterable un-reactive phosphorus in a shallow eutrophic lake following a significant reduction in catchment load. Geoderma, 257-258, 78-85.

Spencer, B., Edwards, D., Kaiser, M. & Richardson, C. 1994, "Spatfalls of the non-native Pacific oyster, Crassostrea gigas, in British waters", *Aquatic Conservation: Marine and Freshwater Ecosystems,* vol. 4, no. 3, pp. 203-217.

Spencer, M. et al. (2011). Temporal change in UK marine communities: trends or regime shifts? Marine Ecology. 32, 10-24.

Stafell I. (2018). Article on-line https://www.drax.com/technology/heatwave-affects-electricity-demand/

Stefan, H. G. *et al*. (2001). Simulated Fish Habitat Changes in North American Lakes in Response to Projected Climate Warming. *Transactions of the American Fisheries Society*, 130, 459-477.

Steinman A.D., Spears B.M. 2020. Internal phosphorus loading in lakes: causes, case studies, and management. J. Ross Publishing. 464p. Fl, USA.

Straw, N.A., Fielding, N.J., Green, G., Price, J., 2005. Defoliation and growth loss in young Sitka spruce following repeated attack by the green spruce aphid , Elatobium abietinum ( Walker ) 213, 349–368. doi:10.1016/j.foreco.2005.04.002

Syvret, M., Fitzgerald, A. & Hoare, P. 2008, "Development of a Pacific oyster aquaculture protocol for the UK: Technical report", *Sea Fish Industry Authority, FIFG Project No,* vol. 7.

Tallis JH (1987). Fire and flood at Holme Moss: erosion processes in an upland blanket mire. Journal of Ecology, 75, 1099-129.

Thomas, F.M., Blank, R., Hartmann, G., 2002. Abiotic and biotic factors and their interactions as causes of oak decline in Central Europe. Forest Pathology 32, 277–307. doi:10.1046/j.1439-0329.2002.00291.x

Thomas, Y., Pouvreau, S., Alunno-Bruscia, M., Barillé, L., Gohin, F., Bryère, P. & Gernez, P. 2016, "Global change and climate-driven invasion of the Pacific oyster (Crassostrea gigas) along European coasts: a bioenergetics modelling approach", *Journal of Biogeography,* vol. 43, no. 3, pp. 568-579.

Trimble AC, Ruesink JL, Dumbauld BR (2009) Factors preventing the recovery of a historically overexploited shellfish species, Ostrea lurida Carpenter. Journal of Shellfish Research 28:97-106

Turner, M.G., Calder, W.J., Cumming, G.S., Hughes, T.P., Jentsch, A., LaDeau, S.L., Lenton, T.M., Shuman, B.N., Turetsky, M.R., Ratajczak, Z. and Williams, J.W., 2020. Climate change, ecosystems and abrupt change: science priorities. Philosophical Transactions of the Royal Society B, 375(1794), p.20190105.

Urli, M., Porté, A.J., Cochard, H., Guengant, Y., Burlett, R., Delzon, S., 2013. Xylem embolism threshold for catastrophic hydraulic failure in angiosperm trees. Tree Physiology 33, 672–683. doi:10.1093/treephys/tpt030

Van Der Meeren, T., and Ivannikov, V. P. 2006. Seasonal shift in spawning of Atlantic cod (Gadus morhua L.) by photoperiod manipulation: Egg quality in relation to temperature and intensive larval rearing. Aquaculture Research, 37: 989–913.

Van Der Spoel, M. (2019). Identifying niche requirements of cylindrospermopsis and nine other common European cyanobacteria genera. University of Edinburgh, GeoSciences, Dissertation, April 2019

Visser P.M., Ibelings B.W., Bormans M and Huisman J (2016) Artificial mixing to control cyanobacterial blooms: a review, https://link.springer.com/article/10.1007/s10452-015-9537-0

Voss, R., Quaas, M.F., Stiasny, M.H., Hänsel, M., Pinto, G.A.S.J., Lehmann, A., Reusch, T.B. and Schmidt, J.O., 2019. Ecological-economic sustainability of the Baltic cod fisheries under ocean warming and acidification. Journal of environmental management, 238, pp.110-118.

Wagner EL, Ruesink JL, Dumbauld BR, Hacker SD, Wisehart LM (2012) Density-dependent effects of an introduced oyster, Crassostrea gigas, on native intertidal eelgrass, Zostera marina. Mar Ecol Prog Ser 468:149-160

Wardlaw I.F and Moncur L (1995) The Response of Wheat to High Temperature Following Anthesis. I. The Rate and Duration of Kernel Filling, Australian Journal of Plant Physiology, 22(3), 391-397.

Waser, A.M., Deuzeman, S., wa Kangeri, A.K., van Winden, E., Postma, J., de Boer, P., van der Meer, J. and Ens, B.J., 2016. Impact on bird fauna of a non-native oyster expanding into blue mussel beds in the Dutch Wadden Sea. Biological Conservation, 202, pp.39-49.

Waters K., Maberly S.C., Clarke S.J., Spears, B.M., Winfield, I.J. (2018). British Wildlife, 29.3, 159-164.

Watson, R., Albon, S., Aspinall, R., Austen, M., Bardgett, B., Bateman, I., Berry, P., Bird, W., Bradbury, R., Brown, C. and Bulloch, J., 2011. UK National ecosystem assessment: technical report. United Nations Environment Programme World Conservation Monitoring Centre.

WFD-UKTAG, 2016. Lake Phosphorus Standards. WFD-UKTAG, Stirling, April 2016. ISBN: 978-1-906934-61-3. Accessed from http://www.wfduk.org/ on 23rd January 2020.

Whittle, A., & Gallego-Sala, A. (2016). Vulnerability of the peatland carbon sink to sea-level rise. Scientific Reports, 6, 28758, 1-11.

Wijsman, J., Dubbeldam, M., De Kluijver, M., Van Zanten, E., Van Stralen, M. & Smaal, A. 2008, "Wegvisproef Japanse oesters in de Oosterschelde. Eindrapportage. Wageningen Imares", *Institute for Marine Resources and Ecosystem Studies.Report CD63/08.CD63/08.Yerseke*.

Winfield, I. J., Adams, C. E., Bean, C. W., Durie, N. C., Fletcher, J. M., Gowans, A. R., Harrod, C., James, J. B., Lyle, A. A., Maitland, P. S., Thompson, C. & Verspoor, E. (2008). Conservation of the vendace (Coregonus albula), the U.K.'s rarest freshwater fish. Advances in Limnology, 63, 547-559.

Winfield, I. J., Fletcher, J. M. & James, J. B. (2004). Conservation ecology of the vendace (*Coregonus albula*) in Bassenthwaite Lake and Derwent Water, U. K. *Annales Zoologici Fennici*, 41, 155-164.

Wolfenson D and Roth Z (2019) Impact of heat stress on cow reproduction and fertility, Animal Frontiers, 9(1), 32-38

Woodland Trust (2016) Keeping Rivers Cool: A Guidance Manual Creating riparian shade for climate change adaptation, http://www.woodlandtrust.org.uk/mediafile/100814410/pg-wt-060216-keeping-rivers-cool.pdf

Worrall, F. and Burt, T., 2004. Time series analysis of long-term river dissolved organic carbon records. Hydrological Processes, 18(5), pp.893-911.

Wright, P.J., Pinnegar, J.K. and Fox, C. (2020) Impacts of climate change on fish, relevant to the coastal and marine environment around the UK. MCCIP Science Review 2020, 354–381. doi: 10.14465/2020.arc16.fsh

Wright, P.J., Régnier, T., Gibb, F.M., Augley, J. and Devalla, S. (2018) Assessing the role of ontogenetic movement in maintaining population structure in fish using otolith microchemistry. Ecology and Evolution, 8, 7907–7920.

Yallop, A.R. and Clutterbuck, B., 2009. Burning issues: The history and ecology of managed fires in the uplands. In Drivers of environmental change in uplands (pp. 199-213). Routledge.

Yamanaka, T., Raffaelli, D. and White, P.C., 2013. Non-linear interactions determine the impact of sea-level rise on estuarine benthic biodiversity and ecosystem processes. *PloS one*, *8*(7), p.e68160.

Yang X., Tian Z., Sun L., Chen B., Tubiello F., and Xu Y (2017) The Impacts of Increased Heath Stress Events on Wheat Yield under Climate Change in China, Climate Change, 140(3-4), 605-620

Yorkshire Dales National Park Authority (2017) Natural Flood Management Measures – a practical guide for farmers, https://www.yorkshiredales.org.uk/__data/assets/pdf_file/0003/1010991/11301_flood_management_guide_WEBx.pdf

Zwerschke, N., van Rein, H., Harrod, C., Reddin, C., Emmerson, M.C., Roberts, D. & O'Connor, N.E. 2018, "Competition between co-occurring invasive and native consumers switches between habitats", *Functional Ecology,* vol. 32, no. 12, pp. 2717-2729.

# 16 Appendix 1 – Additional detail on methods, by habitat.

## 16.1 Freshwaters

### 16.1.1 Literature search – Freshwaters screening assessment

Evidence was gathered using a two-stage Web of Science (WoS) literature search. The original search was conducted on the 25th October 2018, using the following search terms (for studies covering the period 1998 to 2018):

> *(lake* OR river* OR wetland* OR floodplain*) AND (climate* OR driver* OR stressor* OR temperature OR rainfall OR drought) AND (threshold* OR non-linear OR tipping point)*

Results of the search were scrutinised by the project team, and it was concluded that a number of key sources had not been identified. To rectify this, the search terms were augmented, thus:

> *(lake* OR river* OR wetland* OR floodplain*) AND (climate* OR driver* OR stressor* OR temperature OR rainfall OR drought) AND (threshold* OR non-linear OR tipping point OR resilience OR stable state* OR regime shift*)*

After removing all non-biological/ecological/environmental results (i.e. physical, chemical and engineering), as well as non-European results, this search yielded 460, potentially, relevant studies. The titles and abstracts of these studies were then manually searched to assess whether they explicitly dealt with issues of ecological thresholds in fresh waters. After removal of irrelevant studies, 33 separate entries remained for further consideration. At this stage, one more study was removed as it dealt only with physical (water temperature) change, and not subsequent biological impacts.

### 16.1.2 Prioritised impacts – Freshwaters screening assessment

Table 66 below summarises the prioritisation of 18 evidence chains considered for freshwater impacts. Impacts scored 1, 2, or 3 were included and assessed. Those scoring 4, or cases where climate change impacts were not specifically related to an identifiable climatic variable, were excluded as not relevant. This resulted in the selection of five cases for the development of causal chains for further consideration. Two further cases were scored with the potential to develop causal chains, but were not taken further within the scope of this project: temperature effects on salmonids in rivers, and temperature effects on invasive species in lakes.

*Table 66. **Potential impacts in fresh waters**. Priority scores: 1 = Clear biophysical or societal threshold, quantified; 2 = Clear biophysical or societal threshold, but not quantified; 3 = Possible biophysical or societal threshold, uncertain but with high potential impact; 4 = Threshold effects unclear, or low potential impact.*

| Climate stressor | Habitat | Biophysical response | Ecosystem services affected | Priority score |
|---|---|---|---|---|
| Temperature | Lakes | Phytoplankton composition, biomass and blooms | Drinking water, biodiversity, recreation including fishing | 1 |
| Temperature | Lakes | Fish habitat volume | Biodiversity, recreation including fishing | 1 |

| | | | | |
|---|---|---|---|---|
| Temperature | Rivers, streams | Phytoplankton composition, biomass and blooms | Drinking water, biodiversity, recreation | 1 |
| Temperature | Rivers | Impacts on salmonids | Biodiversity, recreational fishing | 1* |
| Temperature | Lakes | Zooplankton composition | Biodiversity | 3 |
| Temperature | Lakes | Invasive species spread | Biodiversity | 3* |
| Climate change (non-specific) | Lakes | Species abundance and composition | Biodiversity, natural capital | 4 |
| Climate change (non-specific) | Wetlands, wet grasslands | Habitat condition | Purification, nutrient retention, biodiversity | 4 |
| Climate change (non-specific) | Freshwater (non-specific) | Fish climatic space | Biodiversity | 4 |
| Rainfall/Drought | Wetlands, wet grasslands | Habitat condition, ecosystem state | Purification, nutrient retention, biodiversity | 4 |
| Rainfall/Drought | Rivers, streams | Food web structure | Biodiversity | 4 |
| Rainfall/Drought | Rivers, streams | Flooding and drought | None specified | 4 |
| Rainfall/Drought | Rivers, streams | Habitat condition | Purification, nutrient retention | 4 |
| Rainfall/Drought | Lakes | Habitat condition | Purification, nutrient retention, biodiversity | 4 |
| Rainfall/Drought | Ponds | Habitat condition | Biodiversity | 4 |
| Rainfall/Drought | Rivers, streams | Water quality, pollutants | Drinking water, biodiversity | 4 |
| Temperature | Lakes | $CO_2$ emissions from lakes | Greenhouse gas emissions | 4 |
| Temperature | Wetlands, wet grasslands | Flooding | Biodiversity | 4 |

* Causal chains not able to be developed within the timeframe of this project

### 16.1.3 Calculation methods – Freshwaters screening assessment & case study

The relationship between air temperature and water temperature was modelled from a 30-year dataset of air and water temperature for Loch Leven. For all impacts in lakes, projected monthly mean air temperatures were converted to water temperature using the following relationship:

$$T_a = (T_w - 0.6343) / 1.1107$$

Where $T_a$ is monthly mean air temperature and $T_w$ is monthly mean water temperature.

## 16.2 Farmlands and grasslands

### 16.2.1 Literature search – Farmlands and grasslands screening assessment

Evidence was gathered for the two NEA broad habitats: Enclosed Farmland and Semi-natural Grasslands. A two-stage Web of Science (WoS) literature search was used. The original search was conducted on the 25th October 2018, using the following search terms (for studies covering the period 1998 to 2018):

> *(farmland* OR grassland* OR agricultur* OR soil* OR land use) AND (climate* OR driver* OR stressor* OR temperature OR rainfall OR drought OR flood*) AND (threshold* OR non-linear OR tipping point OR resilience OR stable state* OR regime shift*)*

The search terms were subsequently modified to incorporate further descriptors for agricultural production as follows:

> *(farm* OR pasture* OR grazing OR arable OR crops OR dairy OR cow* OR sheep OR livestock OR agriculture* OR soil OR grass OR upland) AND (climate* OR driver* OR stressor* OR temperature OR rainfall OR drought OR flood*) AND (threshold* OR non-linear OR tipping point OR resilience OR stable state* OR regime shift*)*

The search produced 12,550 references, but only 150 if restricted to searching the titles. After filtering for geographic location, the list was reduced to 1,642 references. The titles and abstracts of these studies were then manually searched for relevance to this study. The list was supplemented with recommendations from experts familiar with the agricultural literature, and the grey literature. After removal of irrelevant studies, 18 separate entries remained for further consideration.

### 16.2.2 Prioritised impacts – Farmlands and grasslands screening assessment

Table 67 below summarises the prioritisation of five evidence chains considered for agricultural impacts. Impacts scored 1, 2, or 3 were included and assessed. Those scoring 4, or cases where climate change impacts were not specifically related to an identifiable climatic variable, were excluded as not relevant. This resulted in the selection of four cases for the development of causal chains for further consideration.

*Table 67. **Potential impacts in farmland and grassland**. Priority scores: 1 = Clear biophysical or societal threshold, quantified; 2 = Clear biophysical or societal threshold, but not quantified; 3 = Possible biophysical or societal threshold, uncertain but with high potential impact; 4 = Threshold effects unclear, or low potential impact.*

| Climate stressor | Habitat | Biophysical response | Ecosystem services affected | Priority score* |
|---|---|---|---|---|
| Climate Change (Temperature) | Farmland/Grassland | Decrease in milk production | Livestock economics and welfare | 1 |
| Climate Change (Temperature) | Farmland/Grassland | Parasite outbreaks | Grazing livestock economics and welfare | 2 |
| Climate change (Precipitation) | Farmland/Grassland | Soil erosion | Economic and environmental services of soil | 2 |

| | | | | |
|---|---|---|---|---|
| Climate Change (Temperature) | Farmland/Grassland | Decrease in wheat productivity | Agricultural economics | 2 |
| Climate Change (Precipitation) | Farmland/Grassland | Flooding of agricultural land | Crop production, grazing livestock and other agricultural economics | 3 |

### 16.2.3 Calculation methods – Farmlands and grasslands screening assessment and case study

Agricultural data on cattle numbers were obtained from the June 2017 Survey of Agriculture and Horticulture, using the following data sources:

- England: https://www.gov.uk/government/statistical-data-sets/structure-of-the-agricultural-industry-in-england-and-the-uk-at-june - see “English geographical breakdowns - county / unitary authority”
- Scotland: https://www.gov.scot/publications/results-june-2017-scottish-agriculture-census/
- Wales: https://gweddill.gov.wales/statistics-and-research/survey-agricultural-horticulture/?lang=en
- NI: https://www.daera-ni.gov.uk/publications/agricultural-census-northern-ireland-2017

## 16.3 Peatlands

### 16.3.1 Literature search - peatlands screening assessment

The following search terms were used in Web Of Science for peatlands and Mountain, Moors and Heathlands, covering the period 1998 - 2018:

> (peatland* OR moorland* OR heath*) AND (climate* OR driver* OR stressor* OR temperature OR rainfall OR drought OR flood*) AND (threshold* OR non-linear OR tipping point OR resilience OR stable state* OR regime shift*)

This search provided 348 hits; after excluding literature outwith temperate Europe and non-ecological science areas, and after manual searching of titles and abstracts, this provided a shortlist of 21, supplemented with a further 2 studies from the grey literature, and studies suggested by consultation with peatland experts. After more detailed examination, 6 references were deemed relevant for inclusion.

The number of studies which met the search criteria was rather small relative to the amount of published studies that address some aspects of peatland climate-sensitivity, suggesting either that the search terms used were overly restrictive, or that a high proportion of relevant studies did not explicitly consider concepts such as tipping points or thresholds. Therefore we extended the assessment below based on expert knowledge of the subject area within the project team.

### 16.3.2 Prioritised impacts - peatlands screening assessment

The first three chains were deemed high priority and taken forward for more detailed consideration, but subsequently only one was developed for the national screening assessment. Temperature and drought effects are difficult to disentangle, and the valuation approaches to value multiple impacts are still lacking for peatlands. A water table threshold was identified for biodiversity, but the models to link climate with water tables in peatlands are complex and have not been run at national scale to our knowledge, and running such models was outside the scope of the screening assessment. While sea level rise may affect lowland fen communities e.g. in the Norfolk Broads, and it was recognised this may affect plant communities in those habitats, the impacts on carbon sequestration and existing carbon stocks are likely to be minimal. Some of the most rapid carbon-accumulating systems are marine (e.g. Rogers et al. 2019), and other species tolerant of brackish conditions such as *Phragmites australis* have very high primary productivity. Therefore the existing carbon stocks in low-lying coastal freshwater communities and their potential to sequester additional carbon are unlikely to undergo non-linear change.

Table 68 below summarises the prioritisation of four evidence chains considered for moorlands mountains and heaths impacts.  One chain on temperature effects on montane communities was identified as potentially important, but was not developed in this assessment.

*Table 68. **Full table of potential impacts in peatland and mountain, moors and heathland areas.** Priority scores: 1 = Clear biophysical or societal threshold, quantified; 2 = Clear biophysical or societal threshold, but not quantified; 3 = Possible biophysical or societal threshold, uncertain but with high potential impact; 4 = Threshold effects unclear, or low potential impact*

| Climate stressor | Habitat | Biophysical response | Ecosystem services affected | Priority score |
|---|---|---|---|---|
| Temperature | Peatland | Increase in Graminoid abundance and peatland degradation | Carbon sequestration, water quality, Biodiversity | 1 |
| Drought | Peatland | Changes in plant communities /soil processes | Carbon Sequestration, water quality, flooding, fire risk, Biodiversity | 3 |
| Temperature | Montane | Negative impact on plant communities | Biodiversity | 3 |
| Sea Level Rise | Peatland | Negative impact on plant communities | Biodiversity | 4 |

## 16.4 Woodland

### 16.4.1 Literature search - Woodland screening assessment

Evidence was gathered for impacts in woodlands. The search was conducted in Web of Science (WOS), for studies covering the period 1998 to 2018, using the following search terms:

(woodland* OR forest* OR tree*OR oak* OR pine* OR spruce* OR birch* OR ash*) AND (climate* OR driver* OR stressor* OR temperature OR rainfall OR drought OR flood*) AND (threshold* OR non-linear OR tipping point OR resilience OR stable state* OR regime shift*)

The search produced 8,459 references, but only 89 if restricted to searching the titles. After filtering for geographic location, the full list was reduced to 2,155 references. The titles and abstracts of these were searched manually, leaving 22 candidate papers relevant to thresholds, from which five were deemed sufficiently relevant for inclusion. A further reference (Seidl. R. et al. 2017) was added following expert advice from the project team.

### 16.4.2 Prioritised impacts – woodland screening assessment

Table 69 below summarises the prioritisation of three evidence chains considered for impacts on woodland. Impacts scored 1, 2, or 3 were included and are assessed in the sections above. Any scoring 4 were excluded as not relevant, or insufficiently developed to be easily assessed and of relatively low potential impact.

*Table 69. **Full table of potential impacts in woodlands**. Priority scores: 1 = Clear biophysical or societal threshold, quantified; 2 = Clear biophysical or societal threshold, but not quantified; 3 = Possible biophysical or societal threshold, uncertain but with high potential impact; 4 = Threshold effects unclear, or low potential impact.*

| Climate stressor | Habitat | Biophysical response | Societal end-point affected | Priority score |
|---|---|---|---|---|
| Temperature & drought | Oak woodland; Broadleaved woodland; Conifer woodland | Stem cracking – loss of crown density / needles – reduced ring width growth, physiological stress leads to biotic impact. | Productivity, Carbon sequestration | 1 |
| Temperature | Woodland | Introduction and spread of fecund pest/ virulent pathogens.<br>Increase in defoliating pests on spruce and pine (e.g. *Elatobium abietinum*) | Productivity, Carbon sequestration | 2 |
| Climate change (unspecified) | Unmanaged Ancient & semi- | Decline in ecosystem function, little regeneration, low | Biodiversity, recreation | 3* |

| | | | | |
|---|---|---|---|---|
| | natural woodland | resistance to extreme climatic episodes | | |

* Impacts not explored in this assessment

## 16.5 Marine and Coastal margins

### 16.5.1 Literature search – Marine and Coastal margins screening assessment

The following search terms were used in Web Of Science for **Marine** thresholds, covering the period 1998 - 2018:

> (marine OR sea*) AND (climate* OR driver* OR stressor* OR temperature OR acidification) AND (threshold* OR non-linear OR tipping point OR resilience OR stable shift* OR regime shift*)

This search provided 15,707 hits, narrowed down to ca. 1000 hits, after narrowing down based on geographical location. Titles and abstracts were searched manually for relevance, resulting in a short list of 18 to examine in more detail. The list was supplemented by grey literature and expert suggestions, including MCCIP report cards (MCCIP 2017) and CCRA reports (Kovats & Osborne 2016).

The following search terms were used in Web Of Science for **Coastal margins** thresholds, covering the period 1998 - 2018:

> (coastal* OR sand dune* OR shingle OR cliff* OR lagoon* or machair) AND (climate* OR driver* OR stressor* OR temperature OR rainfall OR drought OR sea-level OR flood*) AND (threshold* OR non-linear OR tipping point* OR resilience OR stable state* OR regime shift*)

The search for coastal margins produced 3,792 hits, narrowed down to <500 after exclusion based on geographic location. Titles and abstracts were searched manually for relevance, yielding 33 potentially useful references. The list was supplemented with grey literature.

The Marine and coastal margin lists were combined, yielding 12 references with sufficient relevance to UK thresholds, summarised to seven threshold-based impacts. The relevant impact chains are shown, with priority scores in Table 70.

### 16.5.2 Prioritised impacts – Marine and Coastal margins screening assessment

Table 70 below summarises the prioritisation of seven evidence chains considered for Marine and Coastal margins impacts.

*Table 70. **Full table of potential impacts in marine and coastal areas**. Priority scores: 1 = Clear biophysical or societal threshold, quantified; 2 = Clear biophysical or societal threshold, but not quantified; 3 = Possible biophysical or societal threshold, uncertain but with high potential impact; 4 = Threshold effects unclear, or low potential impact.*

| Climate stressor | Habitat | Biophysical response | Societal end-point affected | Priority score |
|---|---|---|---|---|
| Temperature | Marine | Altered growth & reproduction of cod; Change in Oxygen concentration | Fisheries (Cod), Biodiversity | 1 |
| Sea Level Rise | Marine, Coastal margins | Coastal Flooding | Unspecified | 2 |
| Temperature | Marine | Changes at species and community level | Fisheries, carbon | 2 |
| Sea Level Rise | Marine, Coastal margins | Habitat Condition | Fisheries | 3* |
| Temperature | Marine | Harmful Algal Blooms (HABS) | Water quality, human health, fisheries recreation, | 4 |
| Ocean acidification | Marine | Changes at species and community level | Carbon, water quality, fisheries | 4 |
| Sea Level Rise/Storm surge/River flows | Marine, Coastal margins (Estuaries) | Estuarine morphology | Unspecified | 4 |

* not assessed

### 16.5.3 Methods – Marine and Coastal margins screening assessment

#### Climate data - Present-day ocean temperatures

Reanalysis ocean bottom temperature data covering the period 01/01/1992 to 31/12/2018 come from the NWS (European North West Shelf) Ocean Reanalysis system (available from http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=NORTHWESTSHELF_REANALYSIS_PHY_004_009; for a detailed description see http://resources.marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-009.pdf). The regional ocean model is the FOAM AMM7 (Forecasting Ocean Assimilation Model, 7km resolution Atlantic Margin Model) setup of NEMO (Nucleus for European Modelling of the Ocean) version 3.6, together with the 3DVar NEMOVAR system (version 3) which assimilates observations. Assimilated data are sea surface temperatures together with vertical profiles of temperature and salinity. Lateral open boundary forcing comes from the GloSea5 global ocean reanalysis and at the Baltic margins from the CMEMS Baltic reanalysis. Atmospheric forcing comes from the ERA-Interim atmospheric reanalysis.

### Climate data - Future ocean temperatures

Data from a non-assimilative North-West European Shelf simulation covering the time-period 2000 – 2099 (Tinker, personal communication) were used. The simulation was carried out with the Metoffice AMM7 setup using the NEMOv3.6 model in configuration CO6 (see O'Dea et al., 2017 for details). It has an average horizontal resolution of 7 km and was forced with a global MOHC-HadGEM2-ES simulation using RCP8.5 (business as usual) climate forcing and run from 1972 to 2099. In the analysis, the period 2000-2019 is used as the present-day baseline period. The temperature data was bias corrected against the NWS Ocean Reanalysis data (same resolution) using a reference period of 2000-2019. For the bias correction, a climatology of daily temperatures over a year was calculated at each model grid point as the 7-day running mean of 2000-2019 daily temperatures for both the NWS Ocean Reanalysis data and the future RCP8.5 North-West European Shelf simulation. The offset between the two climatologies was subtracted at each grid point over the time span of the future simulation for each year.

### Determining settlement threshold risk

Past an initiation threshold, ectotherm growth and development increases linearly with temperature. Therefore, the time period needed to achieve a given development stage will vary depending on the experienced temperatures of an individual, and as such, development is best estimated in a cumulative stepwise manner based on daily temperatures experienced. This can be quantified by measuring "degree days".

A single degree day is calculated as:

$$DD = (T - T_0) \text{ for } T > T_0$$

Where DD is the number of degree days, T is the ambient bottom-temperature that the animal is exposed to, and $T_0$ is a threshold temperature below which no evidence development/growth stage occurring. As development stages have particular heat requirement development can be estimated based on accumulated degree days over a given period:

$$Total\ DD = \int_{day\ 1}^{day\ 365} (T - T_0)\ dt \quad \text{for } T > T_0$$

# 17 Appendix 2 – Natural Environment risk descriptors

| **Risk Descriptor** |
| --- |
| 1. 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) |
| 2. Risks to terrestrial species and habitats from pests and pathogens |
| 3. Risks to terrestrial species and habitats from invasive species |
| 4. Opportunities from new species colonisations in terrestrial habitats |
| 5. Risk to soils from changing climatic conditions, including seasonal aridity and wetness. |
| 6. Risks to natural carbon stores and sequestration from changing climatic conditions, including temperature change and water scarcity. |
| 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 and saline intrusion). |
| 8. Risks to agriculture from pests and pathogens |
| 9. Risks to forestry from pests and pathogens |
| 10. Risks to agriculture and forestry from invasive species |
| 11.Opportunities for agricultural and forestry productivity from new/alternative species becoming suitable. |
| 12. Risks to aquifers and agricultural land from sea level rise, saltwater intrusion |
| 13. Risks to freshwater species and habitats from changing climatic conditions and extreme events, including higher water temperatures, flooding, water scarcity and phenological shifts. |
| 14. Risks to freshwater species and habitats from pests, pathogens |
| 15. Risks to freshwater species from invasives |
| 16. Opportunities to freshwater species and habitats from new species colonisations |
| 17. Risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures. |
| 18. Opportunities to marine species, habitats and fisheries from changing climatic conditions |
| 19. Risks to marine species and habitats from pests, pathogens and invasive species |
| 20. Risks and opportunities to coastal species and habitats due to flooding |
| 21. Risks and opportunities to coastal species and habitats due to coastal erosion. |
| 22. Risk to regulating services provided by species and habitats, including pollination, water quality, water regulation and urban cooling |
| 23. Risks and opportunities from climate change to natural heritage and landscape character. |