# D1.2 Final Report

## What climate impacts to the UK would be avoided by limiting global warming to 1.5°C, as compared to higher levels of warming?

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UK Government

CS-NOW

Climate services for a net zero resilient world

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# About CS N0W

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5 million research programme, that will use the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation ambitions.

CS-N0W aims to enhance the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It will contribute to evidence-based climate policy in the UK and internationally, and strengthen the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by **Ricardo** and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL).**

# Executive summary

This report aims to quantify and map projected indicators of climate-related risks across key themes for the United Kingdom in 2050 and 2080 or 2100. The indicators cover climate-related hazards, exposure to climate-related hazards, or risks arising from the exposure to climate-related hazards. No additional adaptation is included, except where it is generally considered in the literature that a certain level of adaptation is inevitable, as in the case of flooding, where significant extensive flood defences already exist and are anticipated to be maintained. The themes covered are high temperatures and human health; hydrological drought; flood risk; terrestrial biodiversity; fisheries; natural capital, agriculture and food security.

For each theme the report assesses what may happen to indicators of climate-related risk between a reference period (typically 1981-2000) and global warming levels of 1.5, 2, 3 and 4°C above pre-industrial levels. To date, the average global temperature on earth has increased by approximately 1.1°C[1]. The amount of further global warming will depend on the extent to which greenhouse gas emissions are reduced. In line with UKCP18 climate change projections and underlying IPCC assessments, global warming levels of 1.5, 2 and 3°C might occur by the 2050s, but a global warming scenario of 4°C is assessed only at the end of the century.

For high temperatures and human health, flood risk, natural capital and food security the indicators of climate-related risk are dependent on socio-economic data, including population change. Where this is the case, data have been taken from the following UK-scale shared socioeconomic pathways (SSPs):

- In SSP2, the UK population reaches 76.6 million by 2050 and 83.2 million by 2080 (this is higher than the 2020-based ONS principal population projection which reaches 71.4 million by 2050 and 71.6 million by 2080). Flood risk is based on a high population scenario as used in the third UK Climate Change Risk Assessment (CCRA3), where UK population reaches 79.6 million by 2050 and 87.8 million by 2080.
- In SSP4, the UK population reaches 71 million by 2050, declining to 68.8 million by 2080 (this is similar to the 2020-based ONS principal population projection until 2060, but becomes lower from 2060 onwards). Flood risk is based on a low population scenario as used in the CCRA3, where UK population reaches 69.5 million by 2050 and 67.7 million by 2080.

The UK-SSPs are assumed to be independent from possible global socioeconomic pathways, although in reality some connections will remain. For this reason, the potential for trade in global food commodities to interact with the risks climate change poses to agriculture is explored separately.

We have identified eleven key findings and provide a summary of ratings of projected changes across key indicators by country (Table ES1). Table ES1 reflects the team’s expert judgement of the relative importance of the projected changes in risk indicators and is not intended to correspond to quantitative limits.

The choice of themes and indicators, focus on the 2050 and 2080 or 2100 timescale, and the selection of SSP2 and SSP4 emerged from co-production workshops with a range of policy makers, including the Department for Energy Security and Net Zero. SSP2 and SSP4 reflect high and low population projections respectively, similar to those used in the CCRA3, and allow uncertainty related to socio-economic change to be considered alongside climate change.

While the report covers a wide range of indicators of climate-related risk other priority risks highlighted in the CCRA3, such as risks to people and the economy from climate-related failure of the power systems or climate-related collapse of distribution networks are not captured here.

We hope that the findings of this report will help the Department for Energy Security and Net Zero, the Department for Environment, Food and Rural Affairs (Defra) and the Climate Change Committee (CCC) to address climate change risks in the UK, to support the fourth UK Climate Change Risk Assessment (CCRA4) process, and to assess the efficacy of adaptation options.

[1] At the time of writing

Key findings are summarised below for 1.5°C versus 3°C. Results for most themes are also presented and compared at 1.5°C versus 2°C and 1.5°C versus 4°C in chapters 2-10 alongside spatial maps.

## Key findings:

1. **Global warming of 3°C is projected to increase heat-related deaths tenfold in England, as compared to a 1980-2000 reference period**. Limiting global warming to 1.5°C in 2080 compared to 3°C in 2080 would avoid 64% of additional heat-related deaths (using the SSP2 population and demographic projections and assuming no additional adaptation).
2. **Global warming of 3°C is projected to increase median hydrological drought severity across all river basins in England and Wales.** Changes in median drought severity and intensity are greatest for the Thames River basin region and the South East England river basin region. At 3.0°C median drought severity increases by 23% in the Thames River basin region and 25% in the South East England river basin region, whilst intensity increases by 11% in the Thames river basin region and 11% in the South East England river basin region (compared to the baseline).
3. **Across all sources (river, surface and coastal) flood risk is projected to increase with climate change.** In the absence of further investment in adaptation (beyond basic maintenance activities), Expected Annual Damages to residential properties associated with flooding is projected to increase almost sixfold if there is a rapid rise in global warming reaching 3°C by the 2050s, before stabilising out to the 2080s; increasing from a central estimate of approximately £500m in the present day (2018) to £2,800m in the 2080s.
4. **At 1.5°C of warming a mean of 13% of species in England and Wales, and 8% of species in Scotland are expected to be at risk of local extinctions, arising from a projected loss of climate suitability (compared with 1961-1990). With 3°C of warming these figures rise to 26% in England and Wales and 15% in Scotland and Northern Ireland. Risk of local extinctions of plants and animals is projected to increase the most south of a line from Aberystwyth (Wales) to Hartlepool (England), especially in southern Wales and the Midlands of England.**
5. **With global warming of 2°C, the distributions of key commercial fish species are projected to shift northward and out of the UK Exclusive Economic Zones (EEZ) causing a reduction of catch potential in hotspots with a loss in fish biomass of around 25% on average in the UK EEZ.** Limiting global warming to 1.5°C rather than 3°C avoids 60 to 71% of the projected loss in fish abundance in the UK EEZ.
6. **Natural capital (which covers 17 ecosystem services in this assessment) is more at risk from climate change than from population growth (SSP2), even when ecological footprints are also considered.** This is owing to the projected distribution in population increases being in and around areas where the loss of ecosystem services has already occurred as opposed to moving into 'natural' areas. An 'ecological footprint' is estimated as the amount of land necessary to support an individual or community. Thus, countries with higher ecological footprints have a greater impact on the land than an equivalently sized population with a smaller footprint. While restraining global warming to 1.5°C is beneficial, the potential increases in natural capital risk are still substantial. The best ways to minimise risks associated with natural capital loss is habitat restoration on degraded land and low-quality agricultural land. This would protect and restore biodiversity and thus also ecosystem services on the landscape immediately surrounding these areas.
7. **For the UK average, theoretical maximum wheat yields are on average projected to increase under the 1.5, 2, and 3°C warming scenarios by 1-5 t/ha, with evidence of levelling off under the 4°C scenario. Actual yields are expected to be much lower than the theoretical maximum as many non-climate related factors are assumed to be ideal and there is large regional variation.** Also, there are significant differences in yield response to climate change across regions, with decrease or plateaus in yield appearing at lower levels of warming in the south and east of the UK, where most wheat is currently grown. Whilst water limitation and heat stress due to climate change are included in the modelling, the effects of crop nutrition, pests, diseases, long–term drought and

other factors not directly influenced by climate are excluded, so increases in yields may be much smaller in some regions, or there could even be declines. It is difficult to quantify the relative impacts of these indirect impacts of climate change. Our results instead define the envelope within which yields may be further constrained by such factors. Without adaptation, such factors are likely to have a greater effect on yields, making it harder to realise the potential yield increases predicted here.

8. **With climate change, climatic crop suitability is projected to alter considerably, with larger changes for greater warming levels.** With 1.5°C warming the temperature and precipitation become suitable for a greater range of crops to be grown outdoors and without irrigation in several regions (South-west and South-central England, South Wales, Northern Ireland, the North-east coastal fringe and Eastern Scotland), while for all other regions, a smaller range of new crops can be grown. This suggests that there is scope for switching crop types as a viable path towards greater resilience of UK agricultural systems to changing local climates. However, projected loss of pollinators (loss of suitable climate space for pollinators since 1961-1990) exceeds 40% in the major agricultural parts of England, even if global warming is held to 1.5°C. $CO_2$ fertilisation, soil suitability and land-use change are not considered in the crop suitability modelling.

9. **Globally, climate change may modify comparative advantages in food production and trade patterns, with tropical regions being adversely affected. In temperate regions, such as W. Europe, if crop production could be increased, exports would increase resulting in positive welfare gains at 3°C versus 1.2°C warming.** The ability to increase crop production depends on the availability of land, for which there are competing demands, and the effects of climate-change (see point 7 above) including long term drought, the rising frequency and severity of short-lived extreme weather events, pests and disease which might offset projected gains in wheat yield.

10. **Based on the indicators of climate-related risk that we have assessed, climate change is projected to provide increasing opportunities for agriculture and food production in the UK, however, realising these opportunities requires significant adaptation efforts.** These opportunities are related to potential increases in wheat and grass yields and increases in the variety of crops that can be grown in several regions of the UK, both of which are greater at 3°C than 1.5°C. However, realising such opportunities would also require a large amount of adaptation to cope with changes in crop suitability, increasing intensity and frequency of droughts, compound events (e.g., sequential waterlogging and drought) and non-climatic factors such as pests and diseases, but could also compensate for potential price rises in imported commodities resulting from declines in crop yields in low latitude regions due to climate change.

11. **Overall, the findings are qualitatively consistent with those presented in the CCRA3 in terms of the nature and general level of risk, even though CCRA3 was based on a much broader range of risk assessment approaches and tools.** This report strengthens and enhances the CCRA3 findings by providing a more detailed spatially specific analysis of various risks based on new, improved, or updated models or data. The results presented here are spatially explicit and cover global warming increments from 1.5 to 4°C in the 2050s and 2080s/2100 (in contrast to the CCRA3 which focused on risks at 2 and 4°C in 2100).

Table ES1: Summary of ratings of projected changes across key climate-related risk indicators by country (England (E), Wales (W), Scotland (S), and Northern Ireland (NI)) under two alternative scenarios in which global warming reaches 1.5°C or 3°C above pre-industrial levels in 2080/2100. * Indicates results regarding SSP2. ** Indicates results assessed in the absence of further adaptation beyond maintenance activities.

| Indicators | Type of Indicator | 1.5°C | | | | 3°C | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | E | W | S | NI | E | W | S | NI |
| **High Temperatures and Health** | | | | | | | | | |
| Heat-related mortality (average annual deaths)* | Climate-related risk | Orange | Orange | Yellow | Yellow | Purple | Red | Yellow | Yellow |
| **Hydrological Drought** | | | | | | | | | |
| Hydrological drought severity | Probability of a climate-related hazard | Orange | Orange | Yellow | | Red | Orange | Yellow | |
| Hydrological drought intensity | Probability of a climate-related hazard | Orange | Orange | Yellow | | Red | Orange | Yellow | |
| **Flood Risk** | | | | | | | | | |
| Flood risk (expected annual damages (£))*, ** | Climate-related risk | Red | Red | Orange | Orange | Purple | Purple | Red | Red |
| **Terrestrial Biodiversity** | | | | | | | | | |
| Local species extinction (all plants and animals) | Exposure to climate-related hazard | Red | Red | Orange | Orange | Purple | Purple | Red | Red |
| Local extinction of pollinators | Exposure to climate-related hazard | Orange | Yellow | Yellow | Yellow | Purple | Purple | Orange | Orange |
| **Marine Environment** | | | | | | | | | |
| Fish distribution | Climate-related hazard | Orange | Orange | Orange | Orange | Red | Red | Red | Red |
| Fish abundance | Climate-related risk | Orange | Orange | Orange | Orange | Red | Red | Red | Red |
| **Natural Capital** | | | | | | | | | |
| Natural capital (no unit)* | Exposure to climate-related hazard | Red | Yellow | Yellow | Yellow | Purple | Yellow | Yellow | Yellow |
| **Agriculture and Food Security** | | | | | | | | | |
| Wheat yield (t/ha) | Climate-related risk | Green | Green | Dark Green | Green | Green | Green | Dark Green | Dark Green |
| Grass yield (t/ha) | Climate-related risk | Green | Green | Green | Green | Green | Green | Green | Green |
| Changes in crop suitability | Climate-related risk | Orange | Orange | Orange | Orange | Orange | Red | Red | Red |
| Wheat crop water requirement | Climate impact | Yellow | Yellow | Green | Green | Red | Yellow | Green | Purple |
| Wheat water productivity | Climate impact | Red | Green | Green | Green | Red | Yellow | Green | Green |

**Key**

| Colour | Change in indicators due to climate change |
|---|---|
| Decreases in risk indicators - Benefits | |
| Dark Green | Large benefit |
| Green | Benefit |
| Increases in risk indicators - Disbenefits | |
| Yellow | Small or no change |
| Orange | Moderate increase |
| Red | Large increase |
| Purple | Very large increase |

**Note**: the terms 'moderate', 'large' and 'very large' are the team's expert judgement of the relative importance of the projected changes in key climate-related risk indicators and are not intended to correspond to quantitative limits.

# Contents

# 1. Introduction

There is an urgent need to assess how climate risk may accrue in the UK with global warming to inform climate change adaptation and mitigation policy. This report provides an assessment, for key themes, of how various indicators of *climate-related risk* accrue in the UK between a reference period and levels of **1.5**, **2**, **3** and **4°C** global warming. The reference period is, where possible, 1981-2000, but in some cases a slightly different past reference year is used owing to existing model and data constraints.

Climate-related risk is the product of exposure of vulnerable systems to climate-related hazards. The definitions of the terms exposure, vulnerability and risk used by the Intergovernmental Panel on Climate Change (IPCC) may be found in the Appendix (section 12.1). Strictly speaking, risk cannot be fully quantified unless the vulnerability of the system is also considered, and full analysis of vulnerabilities is in general extremely challenging. Vulnerability includes aspects of both adaptive capacity and sensitivity. The indicators of *climate-related risk* used in this report include estimates of changes in climate-related hazards, changes in exposure to these climate-related hazards, or and increases in risks themselves.

Some projections relate to changes in climate-related risk indicators that are independent of socioeconomic trends and are projected using static models. In those cases, the climate-related risk indicators relating to different levels of warming are independent of time (i.e., of whether the global warming level is reached in the 2050s or 2080s or 2100). In other cases, climate-related risk indicators may be dynamic (dependent on the pathway to a particular level of warming) or dependent on population or GDP (Gross Domestic Product) in which case climate-related risk indicators are estimated for the 2050s and the 2080s or 2100 separately. In most cases, the UK-scale shared socioeconomic scenarios SSP2 and SSP4 are explored separately.

No additional adaptation is included except in those cases where it is generally considered in the literature that a certain level of adaptation is inevitable, as in the case of flooding, where significant extensive flood defences already exist and are anticipated to be maintained (although planned, more extensive investment to improve defences and reduce risk is excluded).

The themes cover high temperatures and human health; hydrological drought; flood risk; terrestrial biodiversity; fisheries; natural capital, agriculture and food security. A summary of the climate-related risk indicators presented for each theme is shown in Table 1 below.

For each theme, maps are provided showing the distribution of the climate-related risk indicators (such as exposure of land or people to a climate-related hazard) at 1.5°C warming and 3°C global warming. Where feasible this is done by mapping the present-day distribution of the risk indicator in the reference period and providing comparative maps showing the percentage increase in each grid cell (for example, for hydrological drought). In some cases, for example where risk indicators are by definition zero in all (or some) grid cells in the reference period, absolute increases in the risk indicators are provided instead (for example, for heat-related mortality).

For some sectors, indicators of climate-related risk are dependent on population changes. In that case, two alternative scenarios are explored separately. In SSP2, the UK population reaches 76.6 million by 2050 and 84.7 million by 2100. In SSP4, the UK population reaches 71 million by 2050, declining to 63.4 million by 2100 (Pedde et al., 2021). Additional maps are provided for SSP2/4 and 2050/2080/2100 where appropriate.

In addition, the total aggregate, or average (as appropriate) value of each climate-related risk indicator across the UK has been calculated for the reference period and for 1.5, 2, 3 and 4°C warming, and presented as bar charts. Where the scientific method allows or so dictates, results are separated for 2050 and 2080 or 2100 and SSP2 and SSP4. Results are presented for the UK except for hydrological drought, which due to data availability is presented for GB only.

**Table 1:** Themes and climate-related indicators discussed in this report

| Indicators | Type of Indicator | Section |
|---|---|---|
| High Temperatures and Health | | |
| Heat-related mortality (average annual deaths) | Climate-related risk | High temperatures and health |
| Hydrological Drought | | |
| Hydrological drought severity (unit) | Probability of a climate-related hazard | Hydrological drought |
| Hydrological drought intensity (unit) | Probability of a climate-related hazard | Hydrological drought |
| Flood Risk | | |
| Flood risk (Expected Annual Damages (£)) | Climate-related risk | Flood risk |
| Terrestrial Biodiversity | | |
| Local species extinction (all plants and animals) | Exposure to climate-related hazard | Terrestrial biodiversity |
| Local extinction of pollinators | Exposure to climate-related hazard | Terrestrial biodiversity |
| **Marine Environment** | | |
| Fish distribution | Climate-related hazard | Fisheries |
| Fish abundance | Climate-related risk | Fisheries |
| **Natural Capital** | | |
| Natural capital (no unit) | Exposure to climate-related hazard | Natural capital |
| **Agriculture and Food Security** | | |
| Wheat yield (t/ha) | Climate-related risk | Agriculture |
| Grass yield (t/ha) | Climate-related risk | Agriculture |
| Changes in crop suitability | Climate-related risk | Agriculture |
| Wheat crop water requirement | Climate impact | Agriculture and food security (water stress |
| Wheat water productivity | Climate impact | Agriculture and food security (water stress |
| Crop price change | Climate related risk | Agriculture and food security (economic losses |

# 2. High temperatures and health

Climate change is projected to increase high temperatures and the frequency and duration of heatwaves leading to an increase in **heat-related mortality**. Older people, babies, young children, and those with underlying health conditions are the most vulnerable to heat related mortality.

This section provides key messages on **heat-related mortality**. The mortality projections are from the Heat Adaptation and Risk Model (HARM) (Jenkins et al., 2022) and reflect changes in the hazard (daily mean temperature), exposure (the number of people in each area) and the sensitivity of the population to higher temperatures (the mean temperature threshold and rate at which daily mortality will increase for different age group categories). The mortality projections provided here assume that no additional adaptation takes place in the future scenarios and excludes other socio-economic and infrastructure conditions that can affect the spatial pattern and magnitude of heat-related mortality, such as underlying health conditions of those exposed; quality of accommodation or level of air pollution. Further limitations are detailed at the end of the section.

**Key messages**

1. **Global warming of 3°C is projected to increase heat-related deaths tenfold in England compared to the 1980-2000 reference period (figure 1).**

The model projects 6,376 *additional* average annual heat-related deaths in England (compared to the baseline of 678 deaths) with global warming of 3°C in 2080 (using the SSP2 population and demographic projections). An increase in heat related mortality of 940%.

2. **The benefits of stringent mitigation, in terms of limiting the level of global warming to lower versus higher levels is clear for heat-related mortality (figure 1).**

Average annual heat related mortality in the UK increases with each global warming level, particularly at higher warming levels of 3 and 4°C. Limiting global warming to 1.5°C in 2050 compared to 2°C in 2050 avoids 30% of additional heat-related deaths. Limiting global warming to 1.5°C in 2080 compared to 3°C in 2080 would avoid 64% of additional heat-related deaths, whilst limiting global warming to 1.5°C in 2080 compared to 4°C in 2080 would avoid 78% of additional heat-related deaths (using the SSP2 population and demographic projections).

3. **Urban areas with high populations are hotspots for heat related mortality, but as global warming levels increase much larger swathes of England, as well as higher population regions of Wales and Scotland are also affected (Figure 2).**

The model projects 286 *additional* heat-related deaths in Wales (an 818% increase from the baseline); 166 *additional* heat-related deaths in Scotland (a 1059% increase from the baseline); and 39 *additional* heat-related deaths in Northern Ireland (a 1698% increase from the baseline) with global warming of 3°C in 2080 (using the SSP2 population and demographic projections).

4. **Burdens of heat related mortality are much higher in older populations, particularly those aged 85+ (Figure 3).**

Average annual heat related mortality in the 85+ category increases with each global warming level, and particularly at higher warming levels of 3 and 4°C. This reflects the fact that older populations are more vulnerable to more moderate as well as higher increases in temperature.

5. **In the future, alongside climate change, changes in the size and structure of the UKs population that will be exposed to higher temperatures are likely to be an important driver of heat related mortality.**

Model projections using the higher SSP2 population and demographic projections result in higher heat related mortality than seen when using SSP4. Heat-related mortality is projected to be lower in the 2080s versus the 2050s for 1.5 and 2°C warming levels when using SSP4, reflecting longer term declines in population for some UK regions in this pathway.

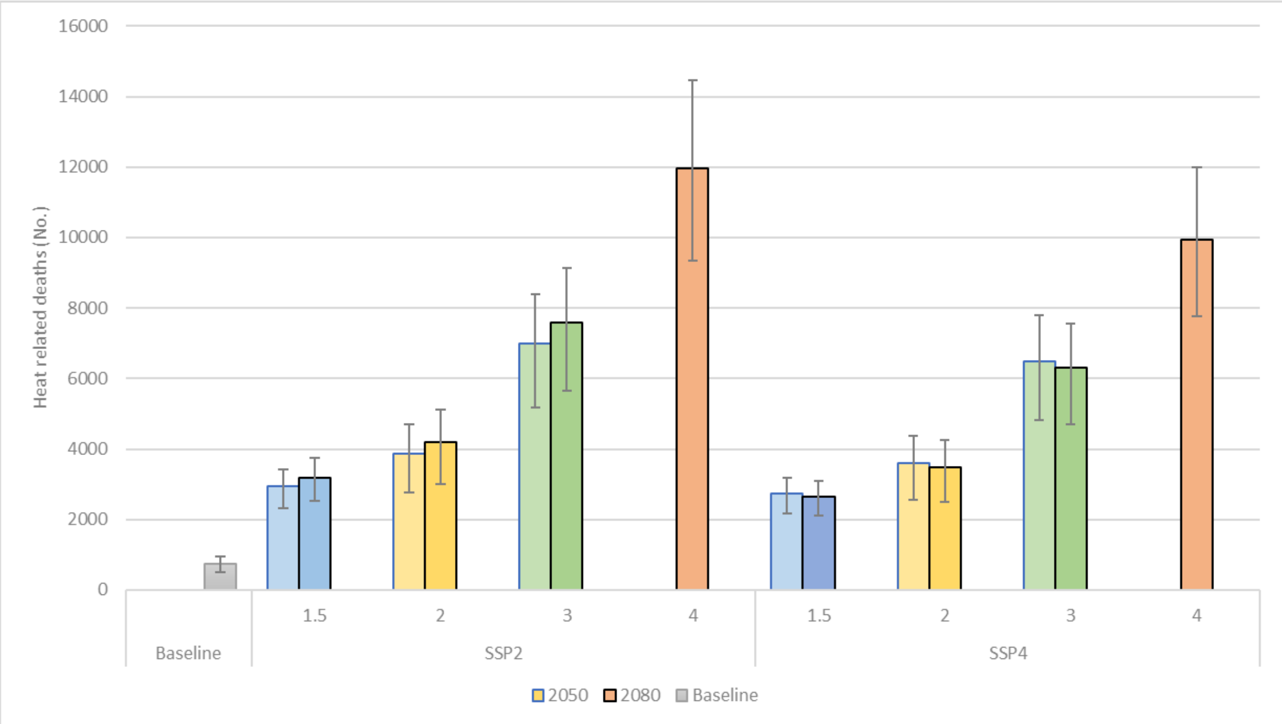


**Figure 1:** Average Annual heat related mortality in the UK due to climate change at warming levels of 1.5 to 4°C and population change (SSP2 and SSP4 in 2050 and 2080). Bars reflect the 12 Regional Climate Model (RCM) ensemble average. The black lines represent 10th and 90th percentiles.

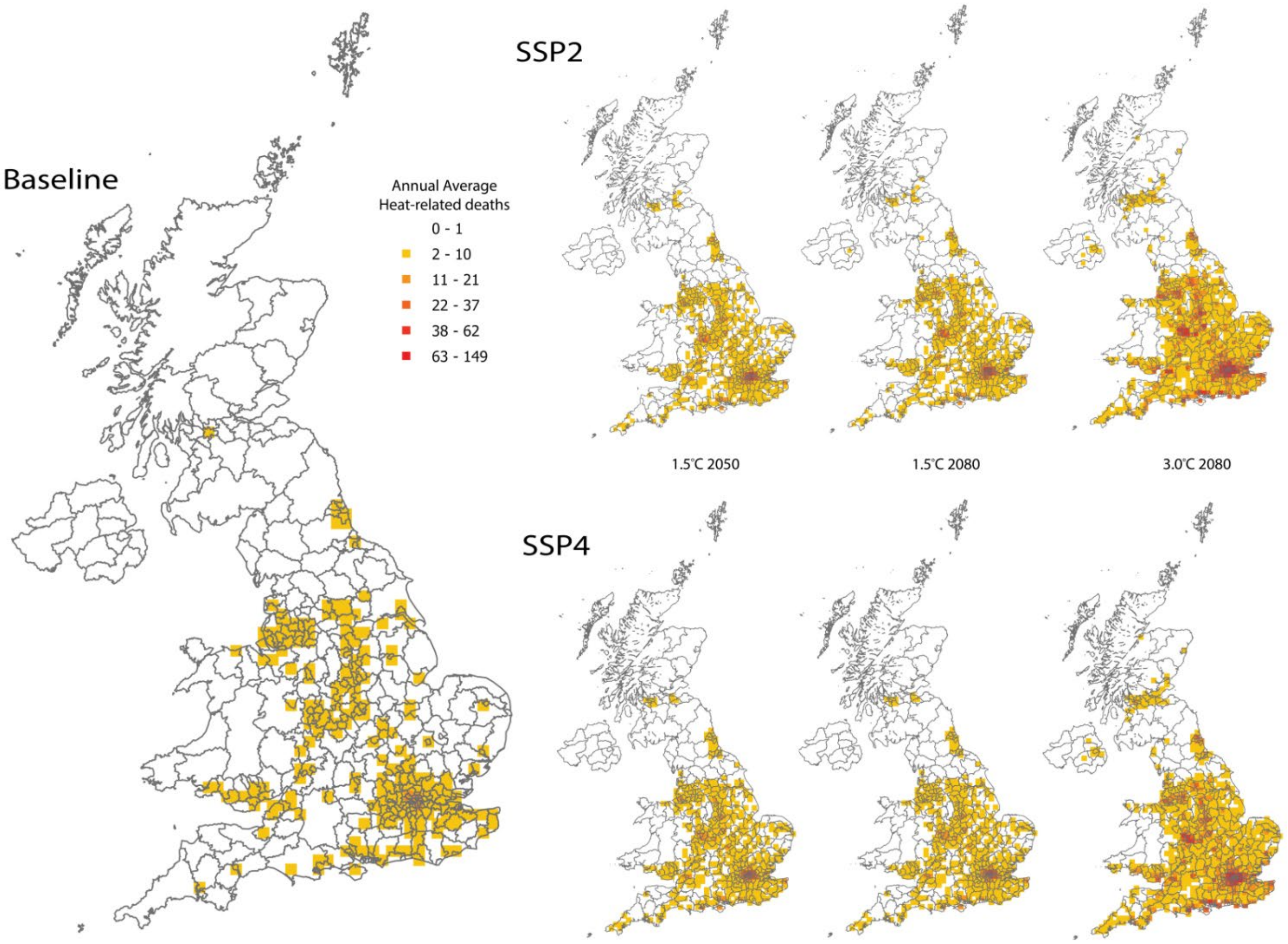


**Figure 2**: Spatial pattern of average annual heat-related deaths in the UK for all ages based on an ensemble of 12 RCM simulations (mean estimates across the 12 RCMs are shown) at 12km. Maps are shown for the 1981-2000 baseline (absolute heat-related deaths) and 1.5°C and 3°C (additional heat-related deaths relative to the baseline). These results consider both climate change and population change in 2050 and 2080 (SSP2 and SSP4). Boundaries represent Local Authority Districts (LADs) shown here for geographical context.

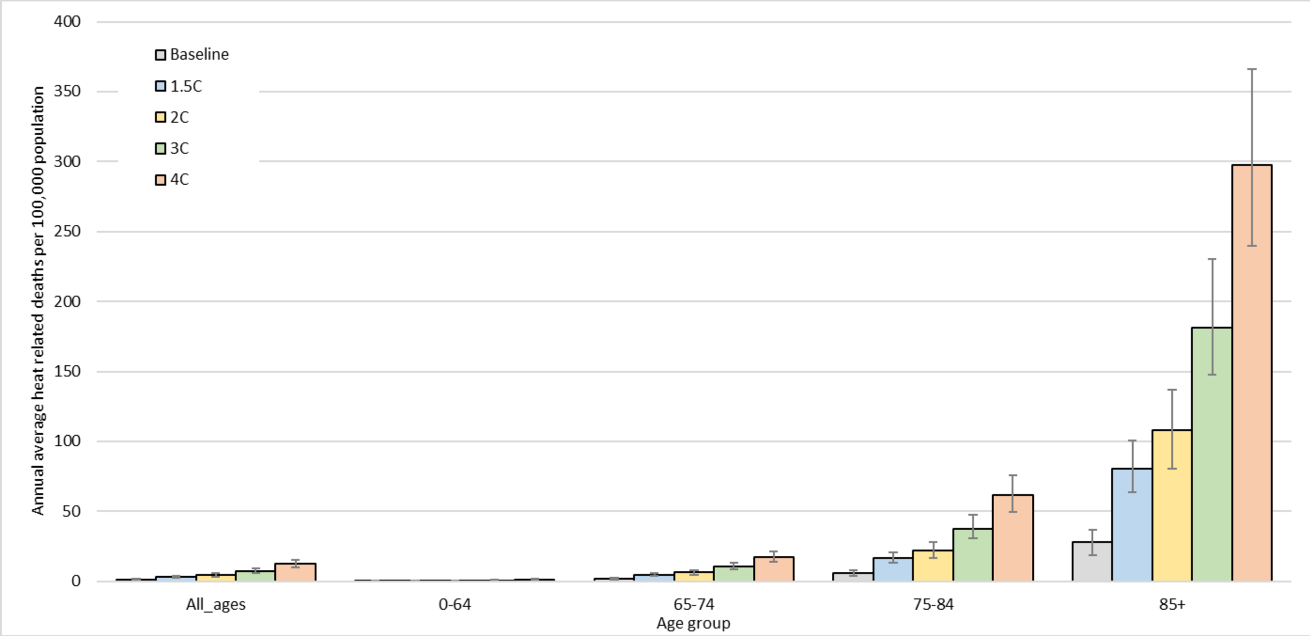


**Figure 3:** Absolute average annual heat-related deaths per 100,000 population per age group (UK-SSP2 2080 for 1.5 to 4°C global warming levels respectively). Bars reflect 12 RCM ensemble average annual heat-related deaths for the past and given global warming levels. The black lines represent 10th and 90th percentiles.

## Caveats and limitations

1. The method uses linear Exposure Response Functions (ERFs) to estimate heat related mortality, which do not consider the nonlinearity in the health response to heat exposure, which is extremely important. A comparison of this method to one using nonlinear ERFs during historical heatwave events in England found total heatwave deaths in England were on average similar (+5.8%) (Jenkins et al., 2022). As such, results above may represent slight overestimates.
2. However, at a local level, other socio-economic and infrastructure conditions can affect the spatial pattern and magnitude of heat-related mortality, such as access to green space; underlying health conditions of those exposed; quality of accommodation; level of air pollution; and any implemented adaptation actions. These factors will be important in determining the vulnerability of the exposed population and providing more robust results.
3. Uncertainty in the estimates presented in figures 1 and 3 reflect uncertainty in the UKCP18 regional climate model projections. As the ERFs were assumed to remain constant in the future, uncertainty related to the extrapolation of the ERFs to future time-periods that go beyond the present-day temperature range is not considered here.
4. The ERFs have been developed based on epidemiological data aggregated across large geographical areas, whereas the underlying spatial pattern in mortality trends is much more heterogeneous. In this regard, results are only illustrative of broad scale distributions of mortality across the UK, reflecting the level of exposure derived from the population data.

# 3. Hydrological drought

Climate change is intensifying the water cycle, bringing more intense rainfall and associated flooding, as well as more intense drought in many regions of the world (IPCC, 2021). Hydrological drought refers to below normal river flow or water levels in lakes, reservoirs, groundwater (Rudd et al., 2017).

This section provides key messages on changes in **hydrological drought duration, intensity and severity**. Drought intensity is the deficit in river flow below a threshold (here, the threshold is the long-term mean monthly flow for the baseline period, Jan 1989 - Dec 2018), drought duration is the length of time in deficit (months) and drought severity is the duration multiplied by the mean drought intensity.

The drought projections are from the Grid-to-Grid (G2G) hydrological model (Kay et al., 2022) reflecting changes to monthly mean river flow. The results presented are standardised so that different river basin regions across the country can be compared (Rudd et al., 2017; Rudd et al., 2019). The Grid-to-Grid model has been driven by the UKCP18 'Regional' projections, with a bias correction applied (Kay et al. 2023). Essentially, the same approach has been applied as with the eFLaG hydrological projections (Hannaford et al. 2023). In this way, the results presented here are comparable to the Grid-to-Grid runs completed within eFLaG – Grid-to-Grid was one of the models applied in eFLaG alongside other river flow models (PDM, GR4J and GR6J) and groundwater models (Aquimod and ZOODRM). It should be noted that, as with eFLaG, this formulation of Grid-to-Grid provides *natural* river flows – that is, it does not include human influences such as reservoirs, abstractions for public water supply or irrigation, or discharges from sewage treatment works. Another Work Package of CS-N0W, WPD2.2, is delivering projections of future water scarcity that includes anthropogenic water management interventions as well as 'natural' runs. This issue is considered further in the 'caveats and limitations' section.

**Key messages**

1. **Global warming of 3°C is projected to increase median drought severity across all river basins in England and Wales (Figure 4).**

With global warming of 1.5°C the median drought severity (compared to the baseline) is projected to increase in Southern and Eastern England. Median drought severity is projected to decrease in much of Scotland. At 3°C all river basin regions in England and Wales see increases in drought severity (compared to the baseline) (Figure 4). A more mixed picture of change is projected for Scotland.

2. **The highest increases in drought severity for 3°C warming are projected to be in the Thames and South East England river basin regions (Figure 4).**

Global warming of 1.5°C is projected to increase the median drought severity (compared to the baseline) by 18% in the Thames river basin region and 26% for the South East England river basin region. At 3.0°C the median drought severity (compared to the baseline) increases by 23% in the Thames and 25% in the South East England river basin region (Figure 4 and Figure 5).

3. **At 3°C southern England is projected to experience the largest change in drought intensity.**

Median drought intensity is projected to decrease in some regions of Scotland and Northern England at 1.5°C compared with the baseline, whereas regions of southern England are projected to see an increase, up to 5% in South East England. At 3°C southern England is projected to experience the largest change in drought intensity, increasing by 11% and 11% in the Thames and South East England river basin regions (Figure 4).

4. **Median drought duration is projected to remain stable for most regions.**

With global warming of 1.5°C median drought duration increases in length by 1 month in the Thames and South East England river basin regions, however, this increase is not seen at 3.0°C. Decreases in drought duration of 1 month are projected for the Humber river basin region at both 1.5°C and 3°C (Figure 4 and Figure 5).

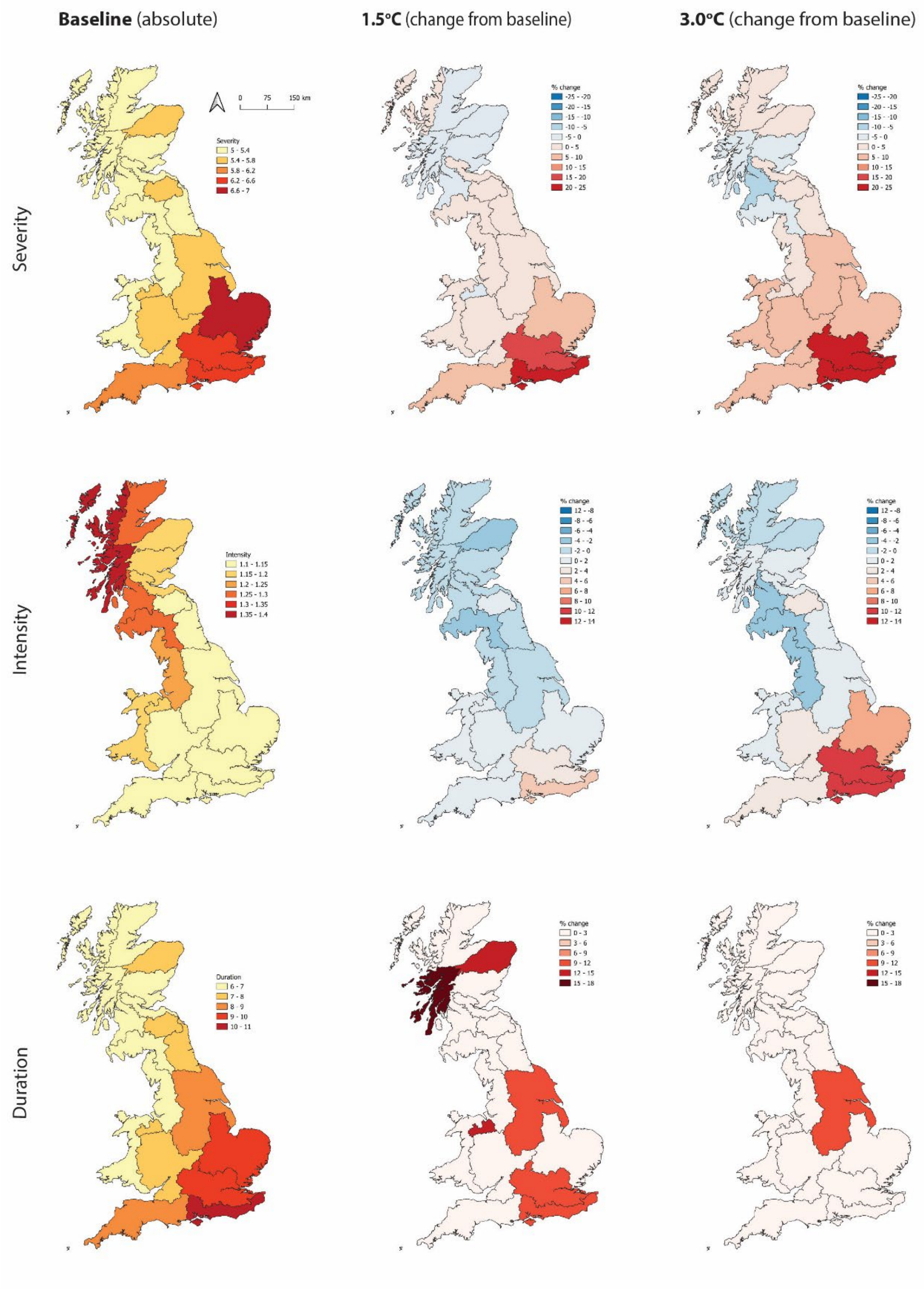


**Figure 4:** Median hydrological drought severity (top), intensity (middle) and duration (bottom). Top panel: Median drought severity for the baseline period and as percentage change from the baseline to 1.5°C and 3°C for 19 river basin regions across GB. Middle panel: Median drought intensity for the baseline period and as percentage change from the baseline to 1.5°C and 3°C. Bottom panel: Median drought duration for the baseline period and as an absolute change from the baseline to 1.5°C and 3°C


**Figure 5:** Median hydrological drought severity (top) intensity (middle) and duration (bottom) for the baseline, 1.5°C, 2°C and 3°C level of warming for 19 river basin regions across the GB.

**Caveats and limitations:**

There are a number of important caveats and limitations that need to be considered. To a great extent, these are the same limitations as with the eFLaG dataset, and these issues are discussed in detail in Hannaford et al. (2023). A short summary is provided here:

- **Climate model uncertainty:** while the UKCP18 Regional projections give a range of 12 possible outcomes (based on a Perturbed Parameter Ensemble), we have simplified the presentation here and presented median changes. Moreover, the Regional projections are only one of the UKCP18 products and do not sample the full range of outcomes in UKCP18. The emissions scenario, RCP8.5, is considered pessimistic and can arguably be seen as a 'worst case' scenario for planning (Arnell et al., 2021). Future work is needed to address hydrological drought projections from a wider range of climate scenarios.

- **Hydrological model uncertainty:** in this study, we have used only one hydrological model, Grid-to-Grid, The eFLaG project uses an ensemble of hydrological models, and demonstrates model choice and model structure is a significant source of uncertainty, particularly for low flows and drought indicators. Hannaford et al. (2023) demonstrate important differences between Grid-to-Grid and several calibrated catchment models, while Parry et al. (2023) and Tanguy et al. (2023) quantify the impact of these differences on future drought and low flow projections. The results presented here should be considered representative of one model, and other models may lead to significant differences in future drought risk.

- Other modelling uncertainties: in addition to climate and hydrological model uncertainties, various other uncertainties can be important in other steps in the modelling chain. These are discussed in detail in Hannaford et al. (2023), and include, for example, uncertainties in input data (e.g., sensitivity to choice of Potential Evaporation formulation) and methodological choices (e.g. choice of bias correction technique).

- Lack of human influences: the Grid-to-Grid setup used here does not include any human influences such as abstractions, discharges or reservoirs, and must therefore be seen as projections of 'natural' river flows and future hydrological drought risk. WPD2.2 of CS-N0W is also providing future projections using Grid-to-Grid, but including abstractions and discharges, which have previously been shown to improve river flow simulations relative to observations (Rameshwaran et al. 2021). WPD2.2 is also projecting future impacts of water management, using socioeconomic scenarios applied to the abstractions and discharges. The scenarios are described in Baron et al. (2023) and the modelling work in Bell et al, (2023). Preliminary analysis of the D2.2 outputs (Tanguy et al. 2023) has demonstrated that while the impact of future changes in abstractions or discharges is smaller than the impact of future anthropogenic warming, changing water management practices are likely to further strongly influence river flows, particularly in some parts of the country.

- Sensitivity to drought definitions: our approach to drought definitions is based on the threshold level method. There are sensitivities in this approach (choice of threshold, approach to pooling events below a threshold). Moreover, drought definition is a complex area and there are many different hydrological drought indicators in use. Other drought definitions and indicators could lead to different results – although the overall direction of future trajectories would be unlikely to be different, so this is a smaller source of uncertainty than others addressed above.

# 4. Flood risk

Across the UK climate change is influencing river flows (Rudd *et al.,* 2023), causing sea levels to rise (Palmer et al., 2018), and increasing the intensity of rainfall (Chan et al., 2021). In response, flood risks are set to change. The change is not likely to be uniform across the UK, but will reflect the complex interaction between spatial changes in the flood hazard (for example in some parts of the UK extreme river flows may reduce) and the change in exposure as some places may experience population growth whilst others experience population decline. Crucially, the magnitude of the change will depend on our success in mitigating climate change and the adaptation actions we take to manage the risk.

This section explores how future flood risk may change. To do so, four climate scenarios (with maximum global warming levels of 1.5°C by the 2030s, 2°C or 3°C by the 2050s, and 4°C by the 2070s) are combined with low and high population projections (Cambridge Econometrics, 2019) and an illustrative assumption of no significant adaptation (e.g., defences are maintained but not raised). It is recognised that investment in adaptation is likely to be much greater than this. For example, HM Treasury and the Environment Agency in England (as well as other devolved nations and private sector organisations) are committed to significant investments in reducing flood risk (e.g. HM Treasury, 2020). Nonetheless, although recognised as an unrealistic scenario, this assumption is used here to frame the assessment of future flood risk in a way that is consistent (as far as possible) with the other risks discussed. The analysis uses the Future Flood Explorer (FFE, Sayers *et al.,* 2020) to quantify the influence of these changes on Expected Annual Damages (EAD) to residential properties (whereby EAD reflects average damages that may be incurred over the course of a year and ignores issues of 'write-off'). The findings are summarised below with key caveats given at the end of the section.

**<u>Key messages</u>**

**1. Mitigation and adaptation are needed to manage flood risk**

All sources of flood risk increase with climate change in the absence of adaptation. Expected Annual Damages to residential properties associated with flooding is projected to increase almost sixfold if there is a rapid rise in global warming reaching 3°C by the 2050s, before stabilising out to the 2080s; increasing from a central estimate of approximately £500m to £2,800m in the 2080s. By the 2080s under a 4°C future the rise is almost eightfold (with EAD rising from around £500m to £3,700m). By the 2080s flood risk is higher under a 4°C future compared to a 3°C future (by a factor of 1.3) and significantly higher compared to a 1.5°C future (by a factor of 20). But the difference is not only evident in the longer term. By the 2050s significant differences in the projected flood risk are already evident depending upon the climate and population future. For example, by the 2050s flood risk is projected to be ~1.5 times higher with global warming trajectory of 4°C (by the 2070s) versus global warming of 1.5°C (by the 2030s) (Figure 6).

**2. River flows (and hence flood risk) have a sensitive and complex relationship with climate change**

River flows are highly sensitive to climate change (Rudd et al, 2023). This sensitivity means the fluvial flood risk by the 2030s is similar regardless of the warming level, with change in risk remaining similar through to the 2080s given a 1.5°C or 2°C rise in global temperature (and not much less than experienced in a 3°C or 4°C world) (Figure 7). This sensitivity suggests that even if the Paris Agreement is achieved fluvial flood risk is likely to increase significantly by the 2080s. This aggregated view masks the variation in the influence of climate change in space across the UK, and in time through the year. For example, in some eastern and southern areas of the UK, climate change is projected to drive a drier climate and may reduce annual damages. Winter fluvial flood risks are expected to increase more, for example, than summer flood risks (Sayers et al, in review). Understanding these spatial and intra-year variations will be important to ensure future adaptations (addressing both drought and flood issues) are well founded.

**3. Sea levels are likely to continue to rise long after global temperatures stabilise**

Reaching 1.5°C by 2030, 2°C or 3°C by 2050 or 4°C by 2070 (rather than by 2100) presents a significant adaptation challenge. Not only does it limit the window for action, but also increases the projected rise in sea levels by 2100 (as sea levels are likely to continue to rise long after global temperatures stabilise). Consequently, coastal flood risk by 2100 is significantly higher if a given global warming level is reached earlier in the century when compared to a slower rise to the same warming level (i.e., the coastal flood risk is higher by 2100 if 2°C is reached by 2050 rather than 2100). Initial analysis suggests sea level rise could be ~10-20% greater by 2100 in these fast rise projections (Jevrejeva et al., 2018) and much greater at intermediate times compared to a slower rise trajectory (Palmer/Lowe personal communication). Incorporating these influences (together with a no adaptation assumption) results in a dramatic increase in coastal flood risk by the 2080s (Figure 7). This emphasises the importance of a long-term time horizon for planning for sea level rise (considerably beyond 2100) and continued investment in coastal defences if future risks are to be well-managed, as well as well-planned and supported relocation in some locations where this may not be feasible (e.g., Sayers et al., 2022).

**4. Surface water flood risks are ubiquitous and set to increase with climate change**

The analysis suggests that surface water flood risks could increase by a factor of ~1.4 (to ~£191m from the present-day baseline set out in the CCRA3, Sayers et al., 2023) and ~1.6 (to £231m) by the 2080s under the 1.5°C and 3°C warming trajectory (and with a minimum adaptation assumption). Surface water flooding is widespread, impacting almost everywhere in the country. Managing future surface water flood risk will require a joined-up approach between public sectors, planners, developers and water companies (as set out by NIC, 2022) as well as continued promotion of Sustainable urban Drainage Systems (SuDS) alongside investment in conventional infrastructure.

**5. Fluvial flood risk is dominant today but in the future coastal flood risk is dominant**.

The EAD associated with fluvial flooding is around ~£250m today, roughly twice that of surface water flooding and three times that of coastal flooding. In the absence of significant adaptation, fluvial flood risks are projected to increase by a factor of ~2.7 (to ~£680m) and ~3.3 (to £830m) by the 2080s under the 1.5°C and 3°C warming trajectory. The assumed fast-paced warming scenarios and the assumption of limited adaptation drive a significant increase in coastal flood risk, rising by a factor of ~12 (to ~£1,000m) and ~20 (to £1,700m) by the 2080s under the 1.5°C and 3°C warming trajectory.

**6. The influence of climate and population change on flood risk varies spatially**

There is significant spatial variation in flood risk across the regions of the UK today. This spatial variation persists into the future, although the increase varies depending upon the sensitivity of the flood hazard to climate change and the local exposure and vulnerability (Figure 8a). The risk is not evenly distributed within each region but also varies significantly. This variation is illustrated in Figure 8b that uses Kernal density plotting approach to present the ‘hotspots’ of increased risk from present day (2018) assuming a 3°C warming trajectory. Estuaries and coasts around the UK can be seen to experience some of the largest increases. This geographic variation has previously been shown to translate into injustice in the risk faced, with the most socially vulnerable experiencing greater flood risk than others today and in the future (Sayers et al., 2017).

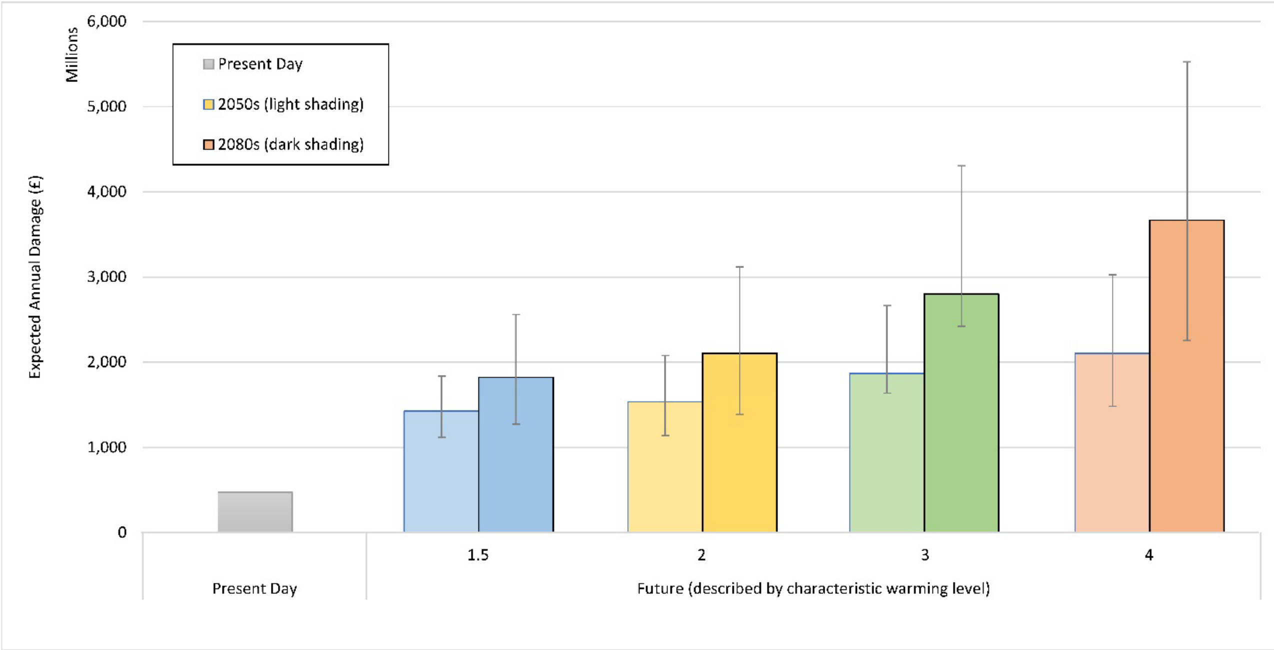


**Figure 6**: UK flood risk – Expected Annual Damage (based on residential direct damages)

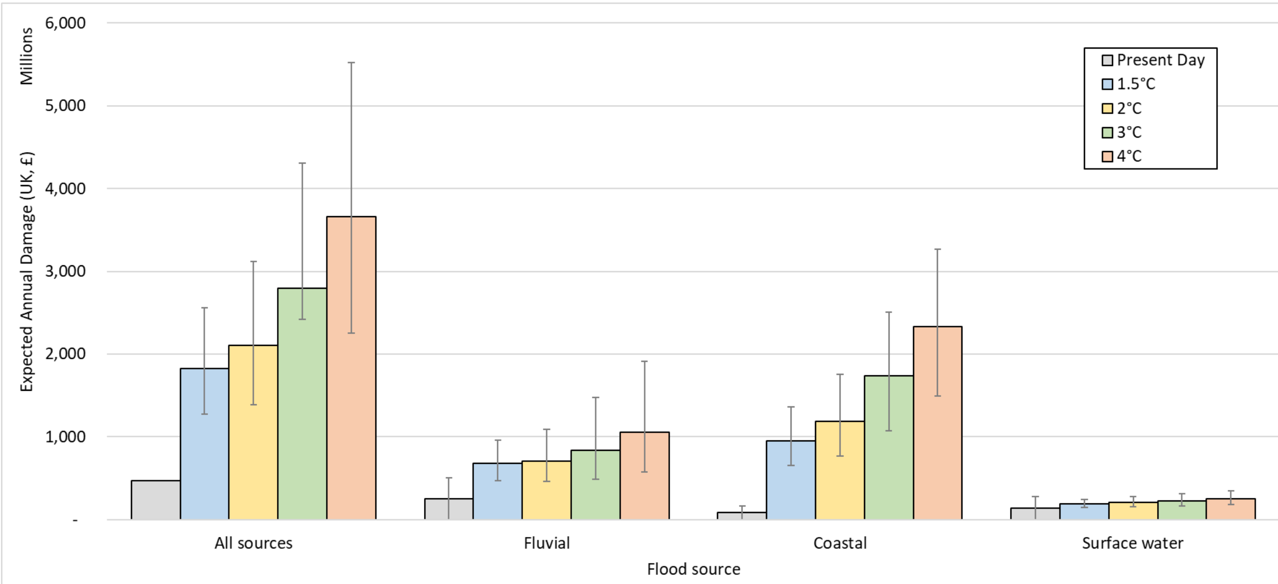


**Figure 7:** UK flood risk by source - Expected Annual Damage (based on residential direct damages)

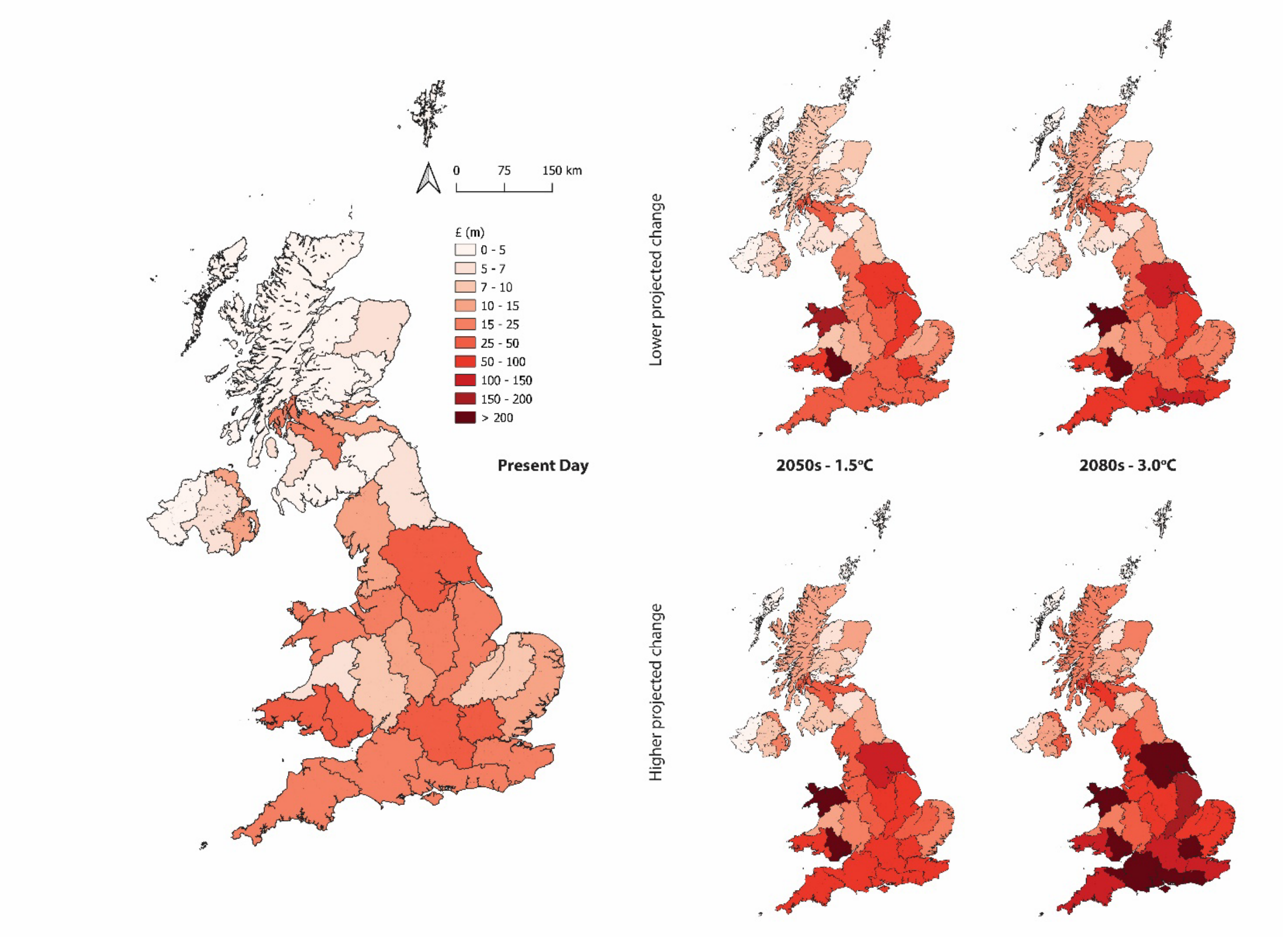


**Figure 8a:** Flood risk – Spatial variation across the UK regions. Present day Expected Annual Damage (based on residential direct damages) and future change given no further adaptation (beyond maintenance of existing defences) and the climate trajectories set out earlier.

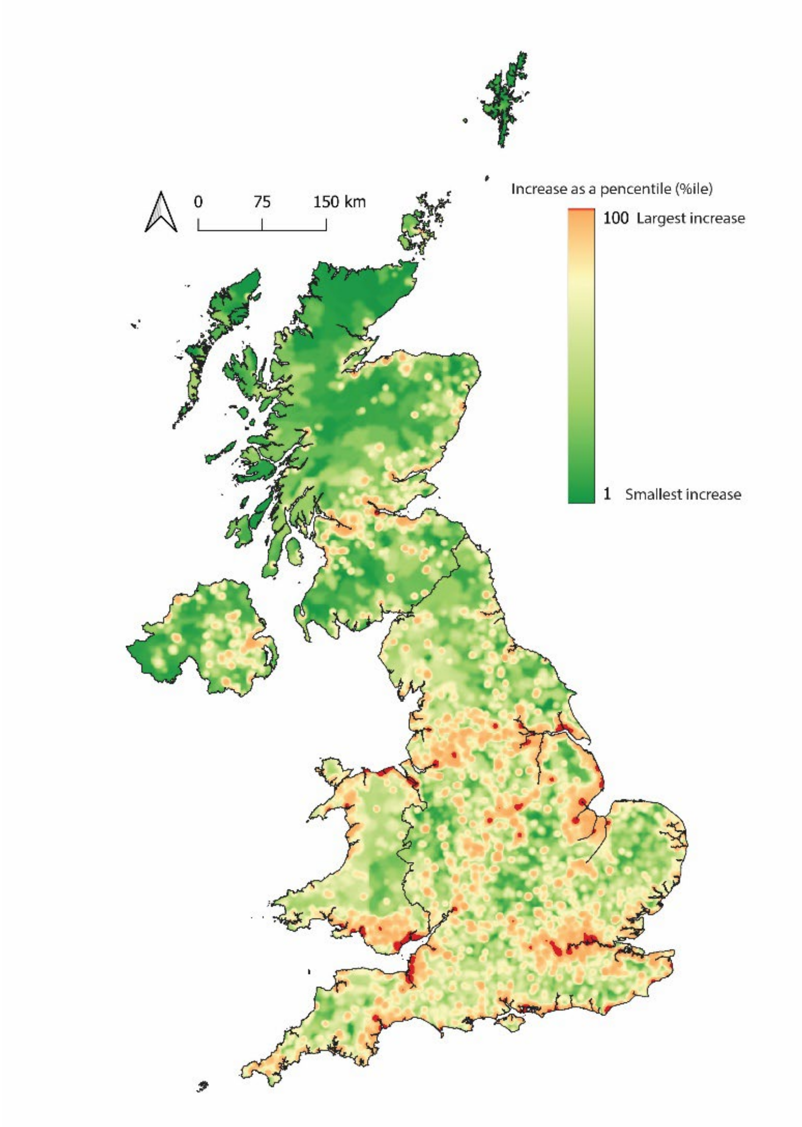


**Figure 8b:** Flood risk – Hotpot assessment of the change in risk from present-day assuming a 3°C warming trajectory. The plot considers the change in Expected Annual Damage (based on residential direct damages) given no further adaptation (beyond maintenance of existing defences). To illustrate the change a Kernal density plotting approach is used (based on 250m grid and 5km radius of influence). The changes values are ranked to project a percentile distribution of the hotspots.

## Caveats and limitations

Although assessment of flood risk is uncertain in detail, there is high confidence that climate change and population growth will lead to a significant increase in flood risk in the absence of sustained investment in adaptation. This includes incremental adaptation to maintain and improve existing defences and enhance the resilience of critical infrastructure networks, communities and individuals, but also transformational adaptation that will be needed to address the most significant challenges, particularly at the coast where sea levels are set to continue to rise for decades, if not centuries, into the future (Le Cozannet et al, 2022). Nonetheless to better understand the context of the analysis presented in this section several important caveats should be noted:

1. **Present day risks:** The estimates of present-day risk are based on data recognised by UK and Devolved Administrations and are assumed credible (as used in support of the UK CCRA3, Sayers et al., 2020). Future changes are projected from this baseline. The uncertainties in the present-day estimates of risk are discussed at length in Sayers et al., 2020, Penning-Rowsell, 2015 and Sayers et al., 2022, as well as in publications from commercial risk providers.
2. **Expansion of the coastal floodplain and property write-off are excluded:** Changes in coastal flood risk are determined through a change in the probability of flooding and associated damages. No attempt is made to cap the value of damage to properties frequently flooded or expand the undefended coastal floodplain as sea level rises.
3. **Climate trajectories:** The future global warming trajectories were set out by the Department for Energy Security and Net Zero and seek to explore what could happen if the rise in global mean surface temperature is rapid and then stabilises. The emerging science basis suggests a more rapid rise in temperature leads to higher sea levels by 2100 than would be the case if the same global mean surface temperature threshold was exceeded later in the century. Quantifying this difference however remains an area of active research.
4. **Adaptation**: The adaptation assumption used here is highly pessimistic and significantly less than current rates of adaptation. This drives a significant increase in risk beyond those presented in CCRA3 (Sayers et al., 2020) that considers more plausible adaptation futures. Nonetheless, the simplicity of the adaptation assumptions used here provides a clear insight into the potential change in risk if we fail to adapt. The assumption made remains physically meaningful, for example, existing defences remain and are not assumed to 'disappear'. Adaptation and investment in reducing surface water flood risk is explored in more detail in Sayers et al., 2023. Incorporating a more realistic representation of adaptation investment, if well-directed, is likely to reduce the uncertainty in future projections of risk, acting to limit the increase due to climate change. Understanding the relationship between adaptation, climate, population and risk will be an important focus of future analysis within the FFE.

# 5. Terrestrial biodiversity

The Earth's regional climate constrains the geographical range of many individual species. The 1.1°C global warming that has so far occurred has already affected biodiversity on every continent. This includes changes in species' geographical ranges, which is the focus on the analysis presented here, as well as changes in the timing of seasonal events (called phenology), and population declines. Increases in the frequency and intensity of extreme weather events are also affecting biodiversity, including both local and global extinctions (see caveats section).

In the future, climate change is projected to affect the distribution of most species on Earth. Large changes in the geographical ranges of species assemblages, in combination with changes in fire regimes and extreme weather events, can lead to loss of ecosystem functioning and can eventually lead to the transformation of one ecosystem into a different type of ecosystem. At the global scale, climatically driven geographic range losses of more than 50% is projected in ~49% of insects, 44% of plants, and 26% of vertebrates for warming of 3.2°C above pre-industrial levels (Warren et al 2018). At 2°C, these projections of loss fall to 18% of insects, 16% of plants, and 8% of vertebrates, and at 1.5°C, to 6% of insects, 8% of plants, and 4% of vertebrates. In this study we downscale this to the UK, looking at the following terrestrial taxonomic groups: fungi, plants, invertebrates (including insects), and vertebrates.

This section provides key messages focused on the UK: increased risk of **local extinction of species per 0.5°C global warming due to climate change alone** for all species studied; projected **species richness loss** (i.e., local extinction) due to loss of suitable climate space since 1961-1990, for insect pollinators (bees, wasps, butterflies, moths, hoverflies, etc.); and the **location and size of places that act as refugia for UK biodiversity as a whole** under climate change. The results show increasing loss of UK species and shrinkage of UK refugia with increasing temperature. Pollinators were chosen as one of the metrics to depict in this report as they are more exposed to climate change than flowering plants in many areas and are necessary for many UK crop species.

Finally, a **prioritisation metric for conservation/restoration efforts** was developed to assist planners and local authorities in potentially prioritising future conservation (e.g., 30% of the land protected by 2030) and tree-planting/habitat restoration schemes (e.g., for carbon storage or biodiversity). Many of these current plans do not take climate change into account and this places those investments at risk.

The analyses presented here do not explore the potential for some species to move to new geographical locations (adaptation by movement) nor potential risks associated with extreme weather events or fire regimes. A full list of caveats and limitations is presented at the end of the section. New maps and discussions of potential dispersal impacts are included in the appendix (chapter 12.2, section 5).

**Key Messages**

1. **Increased risks of local extinction (arising from projected loss of climate suitability since 1961-1990) reaches a mean of 13% for 1.5°C warming in England and Wales, and a mean of 8% in Scotland and Northern Ireland. With 3°C warming these figures rise to 26% in England and Wales and 15% in Scotland and Northern Ireland.**

2. **Increases in local extinction risks for plants and animals are highest south of a line from Aberystwyth (Wales) to Hartlepool (England), especially in southern Wales and the Midlands of England.**

Figure 9 shows the local extinction rate per 0.5°C global warming relative to 1961-1990. In general, the areas facing the greatest local extinction rate (and potential loss of ecosystem services and biodiversity, see section 7: Natural capital) are the midlands south to the coast, and a few areas in East Anglia. There are also high losses in western parts of England, Wales, and Scotland. Aggregating to the devolved administrations reveals that England is projected to have the highest local extinction rate, followed by Wales, Scotland, and Northern Ireland. However, England and Scotland have the same maximum highest projected local extinction rate (7%) owing to loss of climate suitability per 0.5°C.

3. **Projected loss of pollinators (loss of climate suitability since 1961-1990) exceeds 40% in the major agricultural parts of England, even if global warming were held to 1.5°C. Should warming levels reach 3.0°C the loss increases to 60% or higher, and the area exposed to losses extends over more of southern England and into Wales.**

Figures 10 and 11 show the pollinator species richness loss at 1.5°C and 3°C of warming. Figure 10 shows this loss only in habitats classified as natural using the Centre for Ecology and Hydrology classification of remote sensing data for 2020. Figure 11 shows the same except for land classified as agriculture, including improved pastures.

The projected loss of species richness in pollinators is projected to be greater in agricultural areas than in natural areas. The loss of pollinators from most landscapes would potentially have a magnifying effect on the ability of flowering plants to persist in an area under climate change.

Figures 10 and 11 show that many of the agricultural lands in southern England and the Midlands are projected to lose 40% to 60% of the pollinator species richness with only 1.5°C warming. With 3°C warming the losses spread across southern England and Wales with projected losses of 60% to 80% of pollinator species. Affected crops include oilseed rape (partially insect pollinated), brassica, fruits and berries.

4. **Biodiversity protection relies either on conserving existing ecosystems or restoring biodiversity in areas that have been converted to agriculture, but climate change poses risks to these efforts. With global warming levels of 3°C or above, the priority areas for biodiversity conservation/restoration are limited to higher elevations, Wales, northern England or Scotland; if global warming is limited to 1.5°C, more of the UK could be considered in conservation or restoration efforts with lower risks of climate driven failures.**

Figure 12a shows the potential for ecosystem conservation (on natural land) and figure 12b the potential for ecosystem restoration (on agricultural land) at warming levels from 1.5° to 4°C. Areas in green are defined as climate refugia (remaining climatically suitable for >75% of the species) at temperatures of 1.5°C and 2°C; those in blue at 3°C and 4°C. Those shaded white are no data (urban, water and agriculture (map a) or natural (map b)).

Including temperatures of up to 4°C allows an assessment of areas that may be more resilient to climate change and thus more suitable for prioritising given uncertainties, especially uncertainties over lack of extreme events in the models (see caveats). In the maps, as depicted, most areas to conserve or restore would be in northern England or Scotland. The high resolution of the underlying data, however, allows a user to compare areas within a given local authority area as opposed to the UK as a whole. This captures the more localised differences in land cover and elevation.

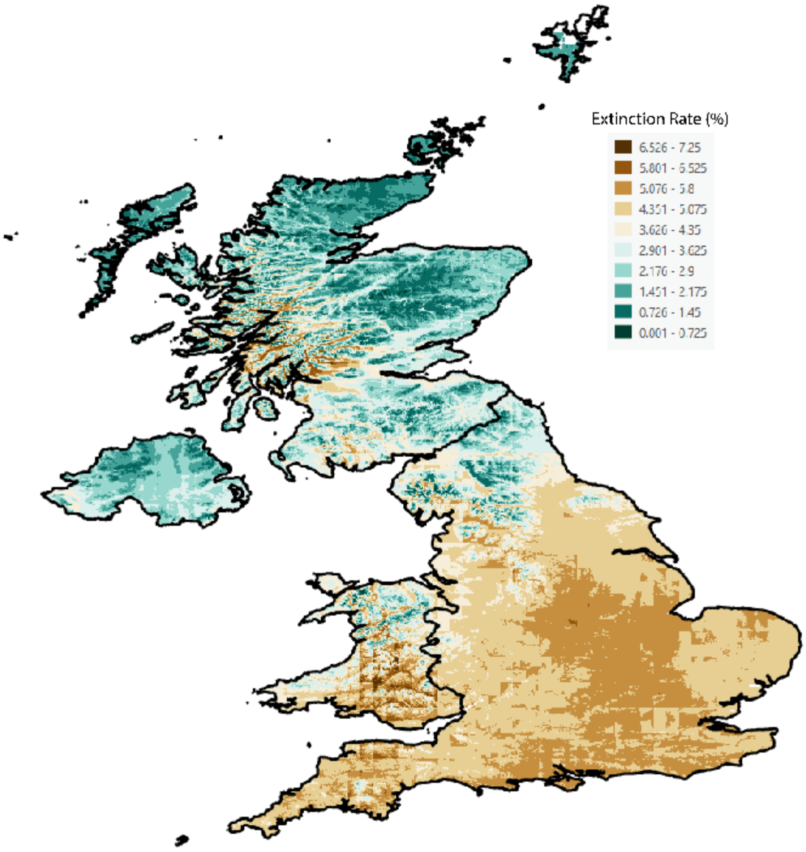


**Figure 9**. Local extinction rate per 0.5°C global warming relative to 1961-1990. Rates range from less than 1% per half-degree warming in the higher elevations to greater than 7% in lower/more southerly locations. Model resolution 1km x 1km, spatial resolution 20m x 20m (see above).

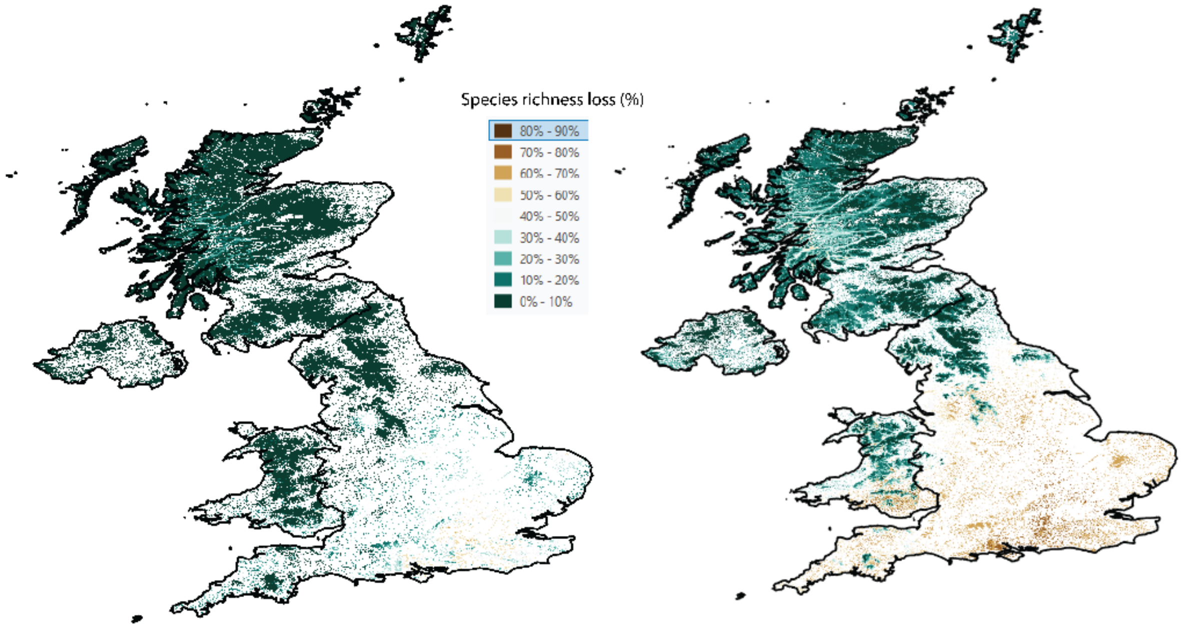


**Figure 10**. Projected climatically driven species richness loss in pollinators (relative to 1961-1990) in land identified on remote sensing (CEH 2020) as natural land. The darker brown, the greater the projected loss of pollinator species. Areas in white are either urban or agricultural land (see Fig 11). Spatial resolution displayed 20mx20m. Note: In Figure 10, the white areas are urban, water, or agricultural. In Figure 11, the white areas are land classified as urban, water, or natural land. This separation makes it easier to delineate the differences in exposure, and their potential consequences, by major land classification type.

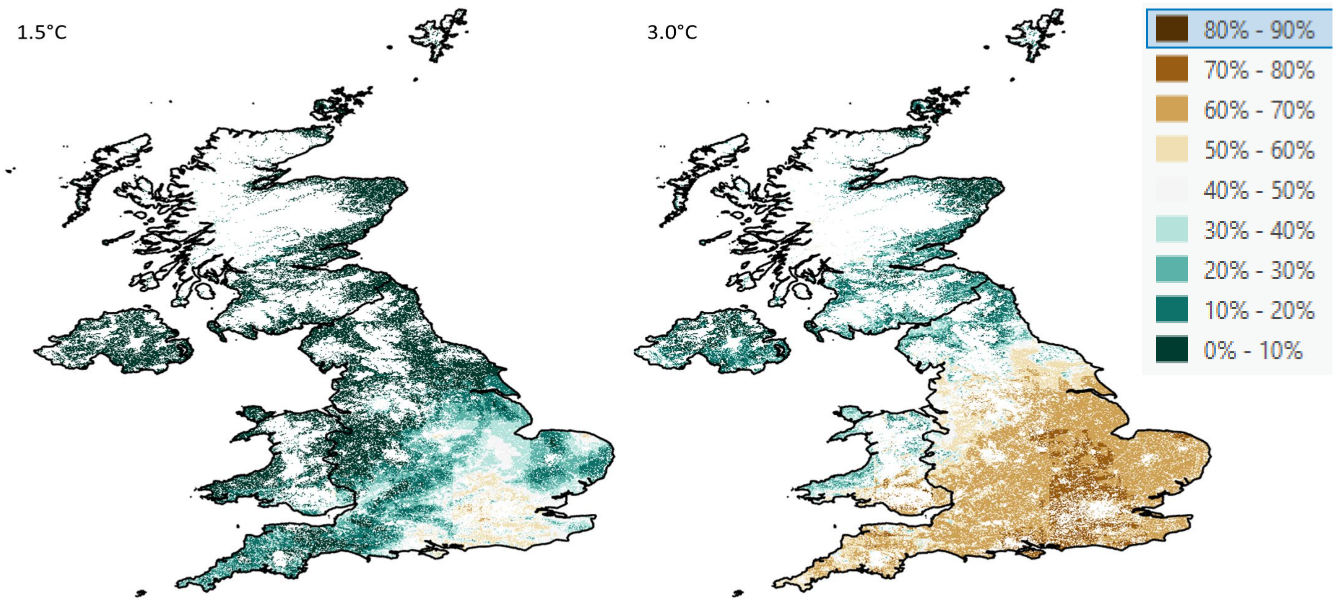


**Figure 11.** Projected climatically driven species richness loss in pollinators (relative to 1961-1990) in land identified on remote sensing (CEH 2020) as agricultural land, including improved pasture. The darker brown, the greater the projected loss of pollinator species. Areas in white are either urban or natural land (see Fig 10). Spatial resolution displayed 20mx20m. Note: In Figure 10, the white areas are urban, water, or agricultural. In Figure 11, the white areas are land classified as urban, water, or natural land. This separation makes it easier to delineate the differences in exposure, and their potential consequences, by major land classification type.

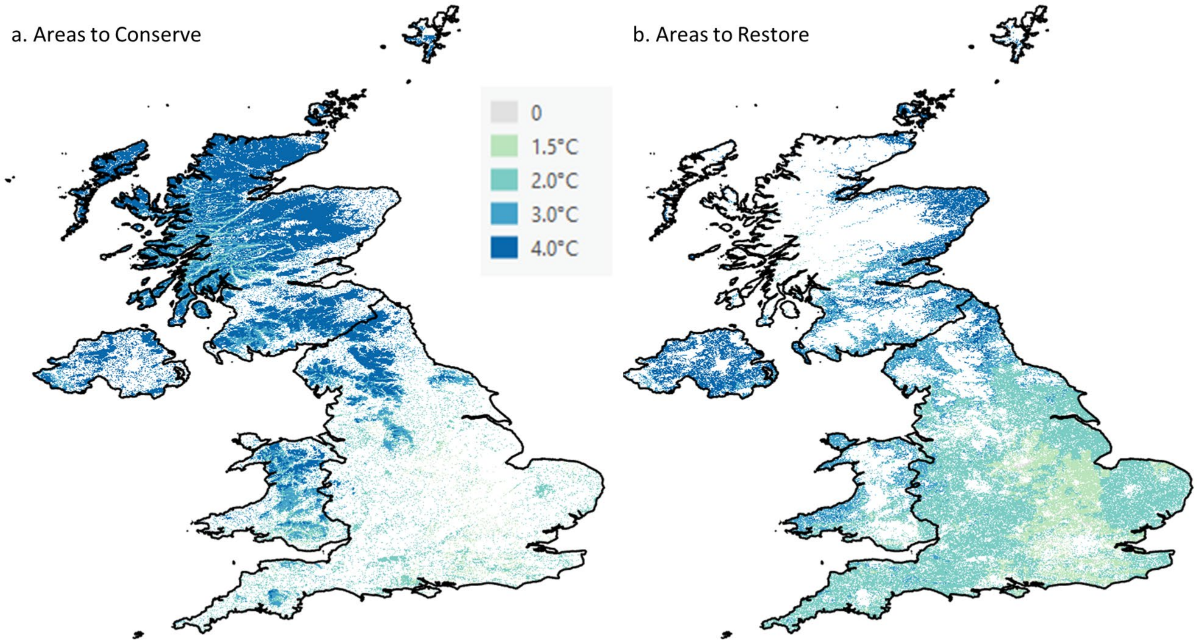


**Figure 12.** Areas to Conserve (a.) and areas to restore (b.) under increasing levels of warming. Areas in green are defined as refugia (remain climatically suitable for >75% of the species currently present) at temperatures of 1.5°C and 2.0°C; those in blue at 3.0°C and 4.0°C. Those shaded white are no data (urban, water and agriculture (map a) or natural (map b).

## Caveats and limitations

1. What is projected is actually the loss of a suitable climate for the species. This means that the species is projected to be lost (i.e., become locally extinct) due to climate change alone and is independent of the land cover and land cover changes that have occurred or may occur in the future. Note that many of the areas projected to lose the most species have already seen biodiversity losses owing to land conversion from natural to agriculture, as these are some of the prime areas for food growing in the UK. The baseline used in the calculations assumes that these losses have not taken place as the climate is suitable for the species. This means some of the species projected to be lost, may already have disappeared from some of the grid cells owing to land use change; and it also means that more species may be lost from grid cells than we project due to future changes in land use that are not modelled.
2. Some species may be more, or less, vulnerable than others to loss of climatic suitability, and this analysis assumes that all species are equally vulnerable. Therefore, local extinctions of some species might be over, or under, estimated relative to others.
3. Our results are likely to be generally conservative, in particular in light of the lack of consideration of extreme events (e.g., drought), the potential disruption of predator-prey, plant-pollinator, mutualistic, or other species-species interactions and the limited evidence that mutualisms may or may not be substituted under climate change. Such disruptions may lead to losses of ecosystem functioning, particularly important in the light of the finding that projected range losses in insects and plants may, in many places, exceed those for birds and mammals that have a greater ability to disperse naturally to track their geographically shifting climate envelope. This means that more species may be lost than we project.
4. Additionally, lack of consideration of potential risks associated with extreme weather events, projected to become more frequent and intense in many regions or fire regimes all may lead to impacts

potentially occurring sooner than models project. This means that more species may be lost than we project.

5. The analyses presented here do not explore the potential for some species to move to new geographical locations (adaptation by movement) under climate change. In some cases, this may lead to an overestimation of species loss, but in most cases, this is not likely. While many mammals and birds have an ability to disperse in this way, plants, reptiles, amphibians and most invertebrates have a substantially reduced ability to do so (Warren et al 2018). Furthermore, many areas in the UK are highly fragmented with settlements, transport networks, and agriculture potentially acting as barriers to movement. The degree to which dispersal may result in the successful shifting of an individual species' range will be affected by their dependency on plants and insects which may have been unable to track the shifting climate and therefore this is excluded from the process of identifying climate refugia that are designed to act as indicators of ecosystem intactness. Dispersal is frequently modelled as an important adaptation for the persistence of individual species. However, at the level of the community, potential changes in competition for limited resources, and/or changes to predator-prey, pollinator and seed dispersal interactions, may counter individual species level benefits. Indeed, this community level transformation may lead to greater impacts than presented here. Additional text (and maps) and dispersal have been added to the appendix (chapter 12.2, section 5). In short, relative to the overall number of species, the number of pioneers/colonizers makes almost no change (<1% of all animals studied) to the overall maps. While some species (including charismatic species) are expected to occur more frequently and eventually colonize, it is small relative to the whole. There have been studies pointing out the importance of existing protected areas for habitats for these pioneers. For some species (e.g., European Spoonbills, Black-necked Stilts) this has certainly been the case, while for others (e.g., European Bee-eaters) is has not.
6. The high-resolution maps in Figure 10 are based on refugia (areas remaining climatically suitable for 75% of the species). Since a greater number of plants and invertebrates have been modelled than other species groups, the refugia tend to represent areas where these two groups tend to persist under climate change. This focus is appropriate as plants and invertebrates provide the habitat and the food for vertebrate species, and also include pollinators, seed dispersers, and species that naturally control pests.
7. The maps, as depicted here, do not show the full level of the information provided. The underlying data, and the underlying GIS maps, has a resolution of 20m x 20m allowing for analyses of very small-scale differences - differences that cannot be seen on an overall map. This does not create a bias in the findings.
8. The impact of pollinator loss depends on which species are lost from an area and whether other pollinators may perform the same function. It also depends on whether the loss of one suite of species may lead to the eventual loss of a second group of species because there is a mutualistic ecological relationship in which one species is dependent on another.

# 6. Fisheries

Climate change is projected to change temperatures and salinity in the marine environment. This in turn is projected to lead to changes in biomass and poleward migration of the more mobile fish species as they strive to stay within the right temperature envelope while maintaining the right set of preferred environmental conditions (habitat).

This section focuses on key commercial fish species. It provides key messages on how climate change is likely to affect the **abundance of fish and their distribution** in the UK EEZ (Exclusive Economic Zones). Fish abundance is defined by how many fish are there, either in a specific area or on average in a region. Fish distribution is defined by where the highest concentration of fish are likely to be found. These projections come from the Size Spectrum – Dynamic Bioclimate Envelope Model (SS-DBEM), a species-specific model that resolves both habitat preferences and population dynamics based on available food in the system (Cheung et al., 2009, Fernandes et al., 2013, Wilson et al., 2021). The model provides spatially explicit fish abundance on an annual basis, this allowed us to derive two key metrics: **abundance and distribution**. As the model is dynamic, it can explore the effect of both the level of global warming, and also the rate of global warming. Two scenarios of warming were explored, one with a slow rate of warming (known as RCP4.5) and one with a faster rate (known as RCP8.5).

The model includes fishing as the Maximum Sustainable Yield (MSY), defined as the amount of fish that can by caught for an indefinite period without the population declining. A MSY of one within the model means that fishing is calculated to happen at MSY, a MSY of 0.6 indicates that fishing is happening below MSY level catching only 60% of the calculated sustainable yield. While, when it comes to fisheries management, the MSY of each stock/species is determined independently, within the model MSY is applied to all species that are modelled here, meaning they all experience the same level of fishing pressure. The level at which fish are removed from the system (fishing pressure) is constant throughout the runs. This means that there is no adjustment to stop fishing a stock that is in decline.

It was not possible to distinguish between the impact of fishing for the two model projections with similar global warming but different fishing pressure. Consequently, we focus here on the effect of the warming and its ”speed”. The level of global warming for the two RCP were evaluated and the relevant decade was extracted for the analysis, decades are in the table below.

Table 1: Global warming levels and the corresponding decades that were extracted for RCP4.5 (slow warming) and RCP8.5 (fast warming).

| | RCP4.5 (slower warming) | RCP8.5 (faster warming) |
|---|---|---|
| 1.5˚C | 2030-2040 | 2020-2030 |
| 2˚C | 2055-2065 | 2040-2050 |
| 3˚C | 2090-2100 | 2060-2070 |
| 4˚C | NA | 2080-2090 |

**Key Messages**

1. **Fish distribution is projected to shift due to both the magnitude and the rate of climate change causing a loss over the whole UK EEZ, which is greater for larger or faster global warming (figure 13).**

By mid-century (around 2050) with global warming of 2°C in either RCP, distributions of key commercial fish species begin to shift northward in the UK EEZ. As warming increases the response of fish becomes more pronounced with many species distribution being moderately to strongly affected resulting in a decrease in the available fish to catch.

2. **Changes are very pronounced if global temperatures rise by 4°C by the end of the century, but less pronounced if global warming is limited to 2°C.**

3. **Under RCP4.5 limiting global warming to 1.5°C rather than 3°C avoids 71% of the projected loss in fish abundance in the UK EEZ. Under RCP8.5 limiting global warming to 1.5°C rather than 3°C avoids 60% of the projected loss in fish abundance in the UK EEZ.**

4. **Faster global warming means a more rapid change in conditions and less chance for the ecosystem to adjust, resulting in higher fish loss at 3˚C global warming under scenario RCP8.5 than under scenario RCP4.5.** This is because a level of 3˚C global warming is reached sooner under RCP8.5 than RCP4.5.

5. **Movement of fish out of the UK EEZ is likely to cause a reduction in fish hotspots.**

This is evidenced by a constriction of the areas of high abundance from offshore toward inshore and the southwest where species from warmer waters will start appearing (figure 14).

6. **Climate risk influences fish abundance even if fishing is managed sustainably (figure 15).**

Fish are far less abundant in 2100 if global temperatures rise by 4°C. All the scenarios considered here constrain fishing pressure to below or close to sustainable levels (Maximum Sustainable Yield, MSY, set to 0.6. 0.8 or 1.1). MSY set to 1.1 explores whether there could be less or no coordination between countries for management of fish stock leading to slight overfishing. At a higher level of MSY than used in the model projections (that is, if fishing were managed less sustainably in the future than it is now), the impact of fishing would be expected to exacerbate the effects of climate change (accelerated loss of fish, see Wilson et al., 2021 for an example in the Western Indian Ocean). On the other hand, reducing fishing pressure to sustainable levels or below, would help fisheries recover from climate change if global temperatures peak and then decline.

7. **If the warming level stays below 2°C, inshore areas are likely to be less affected by the projected fish abundance loss (in comparison to offshore waters). Inshore areas show a loss of less than 10% of the biomass compared to offshore areas with over 50% fish abundance loss.**

8. **Demersal fish are likely to respond more strongly to changes than pelagic fish as their habitat need limits their capacity to follow their preferred habitat.**

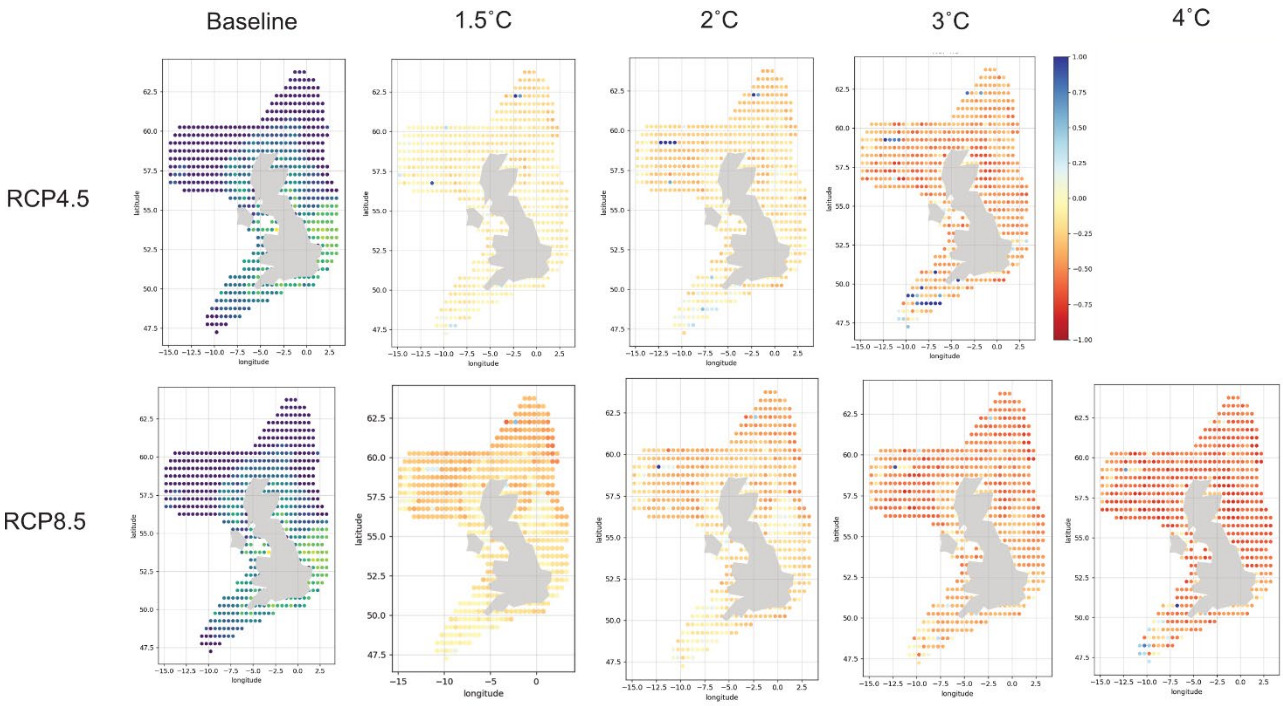


**Figure 13**: Distribution of fish in the UK EEZ for the present period (left column). Abundance was standardised between 0 and 1 to represent the area of high abundance versus low abundance; Columns 2-5 show changes in abundance at different levels of global warming from 1.5, 2, 3 and 4˚C. Top row under the RCP4.5 scenario; bottom row under the RCP8.5 scenario.

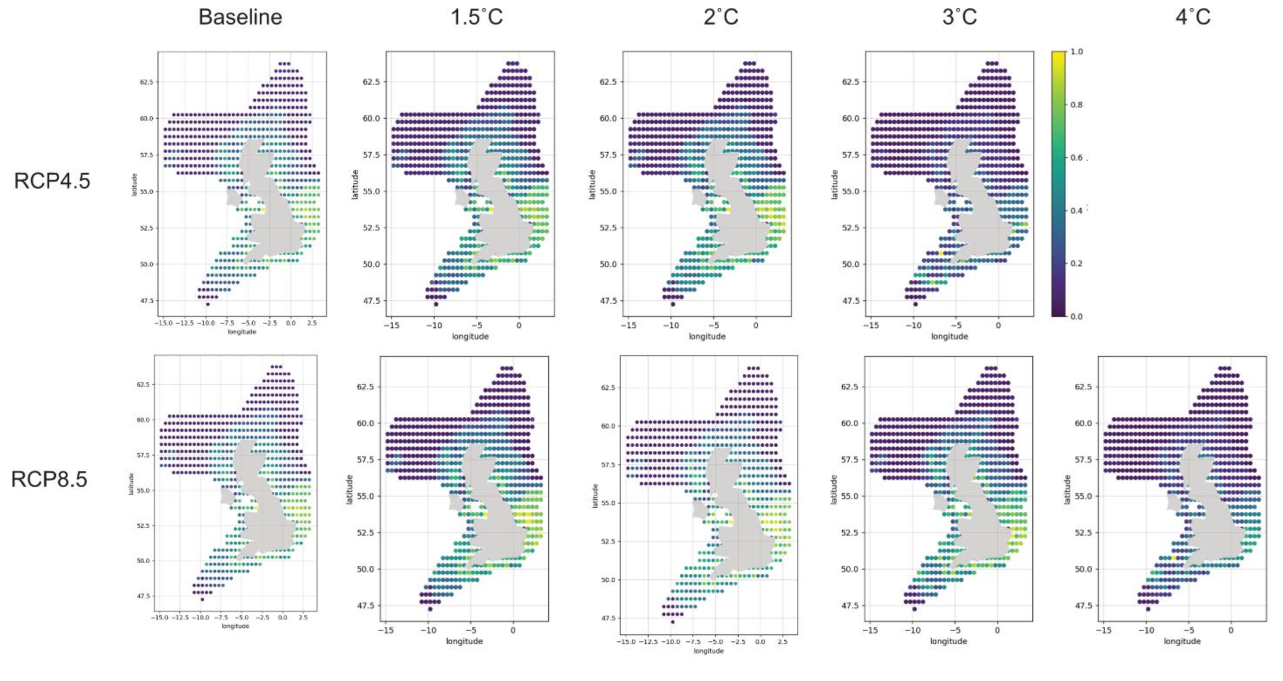


**Figure 14**: Maps of fish distribution using the standardised mean biomass per 10-year time slice to highlight areas of high fish concentration and how these might change in response to climate change and fishing pressure. Left column shows present day baseline (2000-2009). Columns 2-5 show 1.5, 2, 3, and 4˚C warming. Top row: RCP4.5 MSY0.6; bottom row: RCP8.5 MSY1.1.


**Figure 15**: Trends in abundance over time averaged over the whole of the UK EEZ for SSP2, SSP3 and SSP5

**Caveats and limitations**

1. The model resolves fish species rather than biomass in specific size classes, consequently key commercial species were selected and their outputs aggregated to generate these results. Consequently, not all fish species are included and "total fish biomass" is the total biomass of the modelled fish species only. The species considered are listed below, focused on European shelf commercial species:

   **Main species of interest:** Atlantic Cod (*Gadus morhua*), saithe (*Pollachius virens*), haddock (*Melanogrammus aeglefinus*), European hake (*Merluccius merluccius*), Atlantic mackerel (*Scomber scombrus*), Atlantic herring (*Clupea harengus*), common sole (*Solea solea*), European plaice (*Pleuronectes platessa*). **Other species:** Shrimp (*Crangon crangon*), turbot (*Scophthalmus maximus*), common dab (*Limanda limanda*), veined Squid (*Loligo forbesii*), common cuttlefish (*Sepia officinalis*), European squid (*Loligo vulgaris*), blue whiting (*Micromesistius poutassou*), capelin (*Mallotus villosus*), Atlantic horse mackerel (*Trachurus trachurus*), European sprat (*Sprattus sprattus*), red mullet (*Mullus barbatus*), Atlantic halibut (*Hippoglossus hippoglossus*), European seabass (*Dicentrachurs labrax*), Atlantic salmon (*Salmo salar*), meagre (*Argyrosomus regius*), gilt-head seabream (*Sparus aurata*), European sardine (*Sardina pilchardus*), European anchovy (*Engraulis encrasicolus*), common dolphinfish (*Coryphaena hippurus*), Bluefin tuna (*Thunnus thynnus*).

2. The level at which fish are removed from the system (fishing pressure) is constant throughout the runs. This means that there is no adjustment to stop fishing a stock that is in decline.

3. The simulations do not explore the consequences of unsustainably high fishing pressure, and do not consider situations with unregulated and unreported fishing which could increase risks.

4. It is to be noted that if the model was run with a completely different set of climate forcings there would be slight variations in the changes in fish abundance and distribution.

5. The projections do not consider changes in habitats brought by different uses of the marine space like establishment of offshore windfarms, dredging, or dumping.

# 7. Natural capital

The natural environment, such as forests, fisheries and biodiversity, constitutes our natural capital, which directly or indirectly produces goods and services for society (Berry et al., 2021). Natural capital can include both living and non-living components of the natural environment.

Natural capital risk due to the combination of climate change and population growth, assuming 2015 land use persists in the future, is estimated here by a weighted sum of the risks to 17 ecosystem services. These risks arise due to the biodiversity loss presented in section 5 above, other projected changes in climate, such as meteorological drought, and changes in population and associated pressure on natural resources. Human population size is directly linked to current impacts on biodiversity primarily through land conversion (but also unsustainable direct use of biodiversity and pollution, among others). As populations grow in areas it is projected that the impacts will be in line with that already seen with equivalent growth elsewhere. As ecosystem services are now primarily defined as services for humans then the natural capital represents how well the services can 'do their job'. It is possible for the natural capital to be 'overdrawn' and this directly and indirectly impacts the surrounding population.

The ecosystem services considered here are: Food (agriculture), Carbon, Stewardship, Timber, Pest Control, Pollination, Seed Dispersal, Soil Production, Flood Protection, Wild Food/Medicine, Biodiversity, Nature-based Recreation, Aesthetic/Existence Value, Cleaning the Air, Cleaning the Water, Cooling the Air, and Habitat (Price et al. *In Review*).

**Key Messages**

1. **Natural Capital is more at risk from climate change than from population growth, even with ecological footprint taken into account.**

While keeping warming to 1.5°C is beneficial (relative to higher warming levels), the potential increases in natural capital risk are still substantial. The reason for this is that the population growth models used here (and in the IPCC) assume that human population will continue to increase in areas where it is currently increasing, and decrease in areas where it is currently decreasing. While it is accepted that some ecosystem service recovery may occur in areas with population declines, there will still need to be food grown to export to growing population centers. Thus, as the projected distribution in population increases is projected to be in and around areas where the loss of ecosystem services has already occurred, these would show a higher risk category. An 'ecological footprint' is estimated as the amount of land necessary to support an individual or community. Thus, countries with higher ecological footprints have a greater impact on the land than an equivalently sized population with a smaller footprint. While restraining global warming to 1.5°C is beneficial, the potential increases in natural capital risk are still substantial.

2. **The best ways to minimise risks associated with natural capital loss are a) habitat restoration on degraded land and low-quality agricultural land and b) reduction in the ecological footprint.**

This would restore ecosystem services on the landscape immediately surrounding these areas and ecological footprint reduction which would have benefits outside of the UK as well.

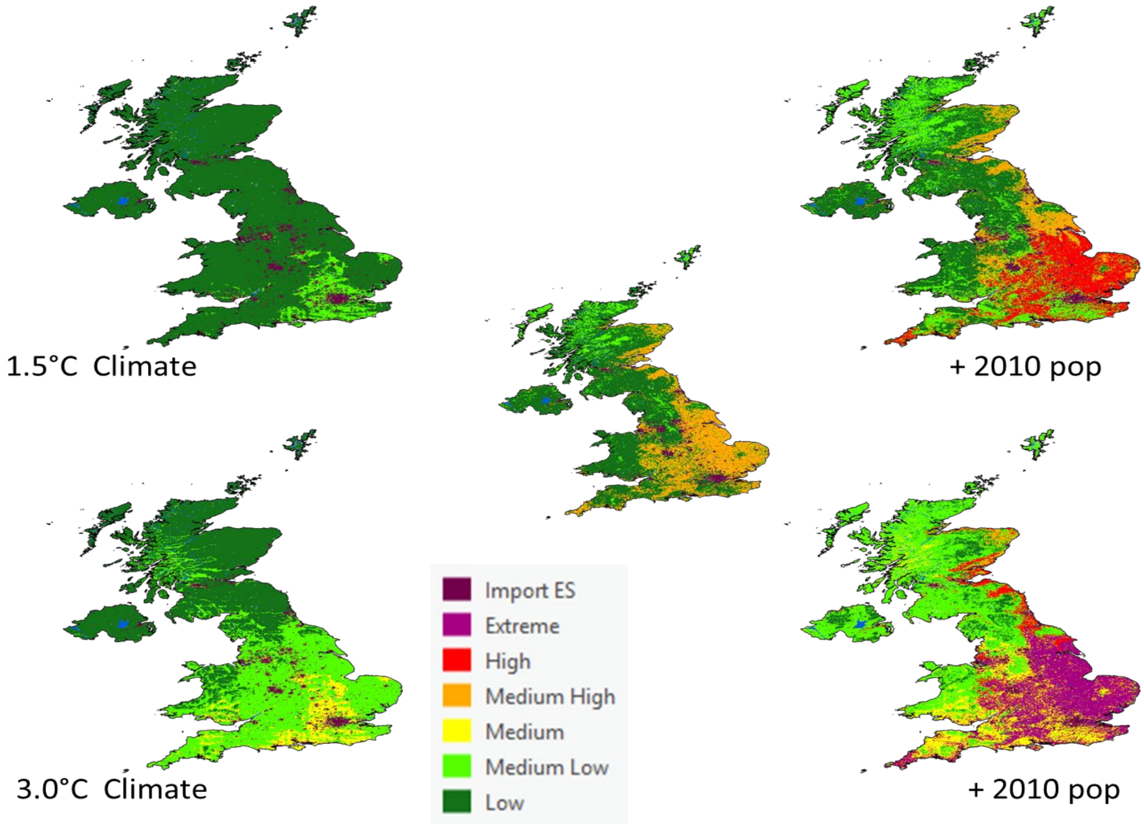


**Figure 16:** Natural Capital Risk owing to Climate Change based on the population in 2010. The left hand maps are an assessment of risk owing to climate change alone (e.g., loss of climate suitability for species) at 1.5° (top left) and 3.0° (bottom left). The central figure is the 'base' ecosystem services in 2015 based on the ESA-CCI land cover map of 2015. By combining the climate maps (left), the land cover map (center) and population density (right) an overall natural capital climate change risk metric can be presented at 1.5° (top right) and 3.0° (bottom right). Spatial resolution is 300m x 300m. Colours indicate the level of risk, with dark and light green representing the lowest risk categories and dark and light purple the highest. Red, orange and yellow areas represent high, medium high and medium levels of risk.

Figure 16 shows relative contribution of climate change and population growth to natural capital risk. The central map shows the baseline risks to natural capital (using 2010 population and 2015 land cover, with a 1961-1990 climate). If one draws an imaginary line from Cardiff to Hull then natural capital in much of the UK below this line is estimated to be at medium high risk owing to current land cover and uses (agriculture/settlements)

The left-hand pair of maps in Figure 16 shows risks to natural capital with 1.5°C or 3°C warming respectively but excluding effects of land use and the human population, while the right-hand pair show risks for the two warming levels including also the effects of land use (2015) and population (2010). Risks to natural capital become high at 1.5°C and extreme at 3°C, with the high-risk zone continuing up the east coast as far as Scotland.

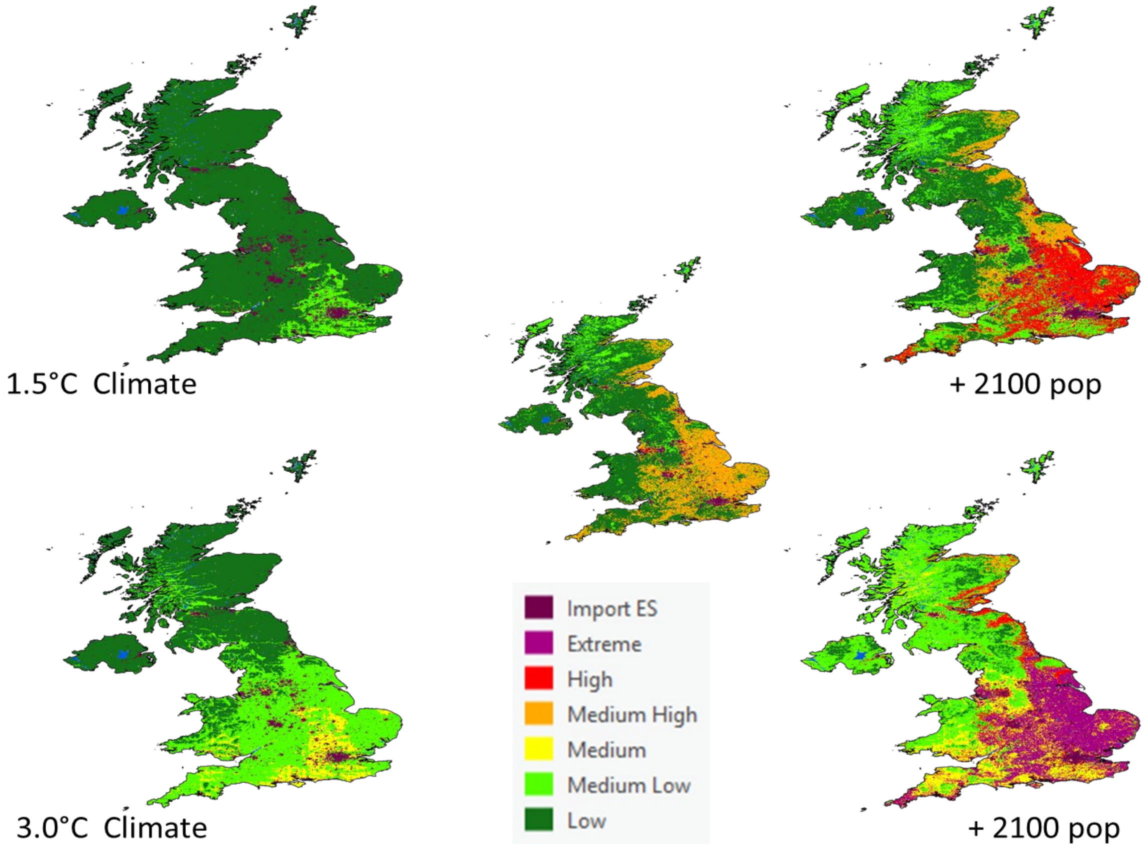


**Figure 17:** As above but using the global population growth projections from SSP2.

Figure 17 is as Figure 16, but the population projection is for 2100 (SSP2). The increase in population would lead to some changes in risk, especially around areas that are currently settled, but these differences are difficult to see in the figure and mostly apparent only when examined at higher resolution (e.g., by zooming in).

Figure 18 considers the additional contribution of the current ecological footprint of the UK (the way the country uses its ecological resources). This means that some areas that were classified at high risk with 1.5°C warming are now at very high risk, and many areas that were at very high risk with 3.0°C warming are now at extreme risk.

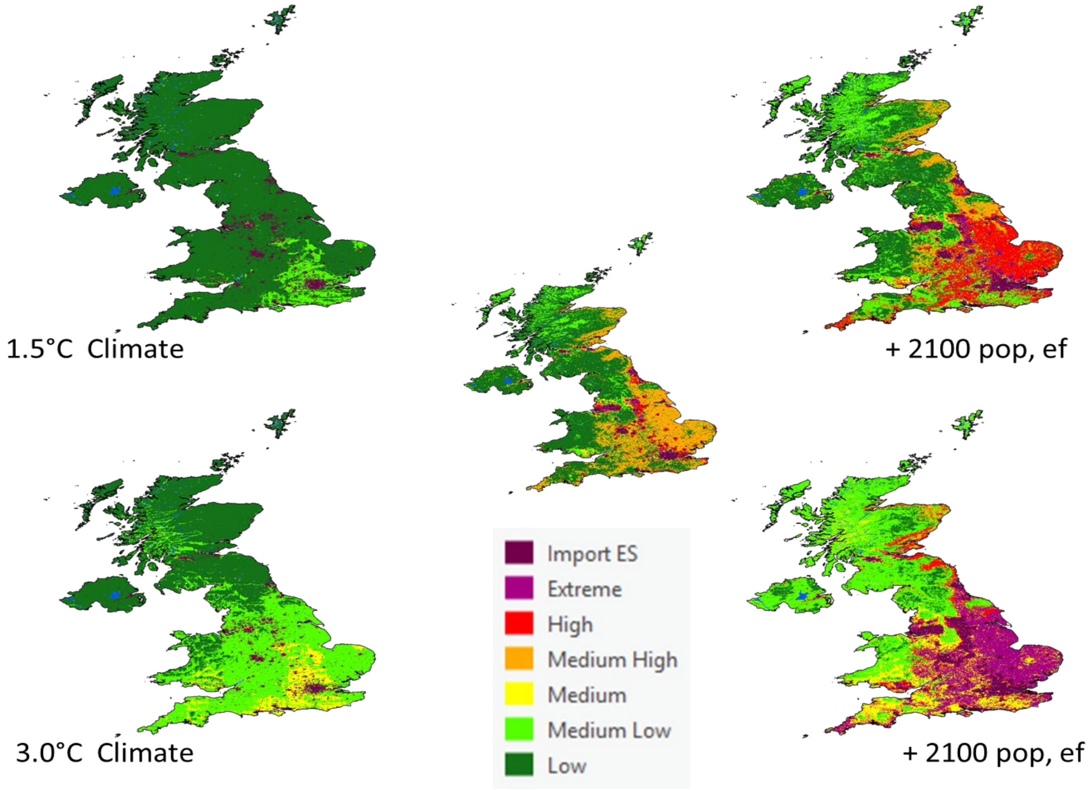


**Figure 18:** As above but using the current UK ecological footprint (figure 17 assumed an ecological footprint of 1). The greater the use of natural resources the greater the risk to natural capital.

## Caveats and limitations

1. Estimates of natural capital risk depend on the choice of ecosystem services that are included and the definition of these services, as well as thresholds set for risks to these services. This study uses one commonly used suite of ecosystem services. There is also a methodological choice on the relative weights of different ecosystem services and the scoring system used for risk.
2. The population growth presented is for SSP2. Using different population projections, different SSPs, or making different assumptions on ecological footprint would yield somewhat different results.
3. The latest year of downscaled population data available for use in this project was 2010, whereas the land use reference point is 2015. This small discrepancy does not affect the key message.
4. These are the first generation of Tyndall Centre's estimates of natural capital risk. A second generation of natural capital simulations is being developed as part of the OpenCLIM project which will draw directly on model outputs similar to those presented in other sections of this report, but results are not available at this time. Improvements will include: higher spatial resolution (20m x 20m, based on Centre for Ecology and Hydrology Land Cover map), potential crop suitability replacing the drought metric SPEI12 as an indicator of risks to food (agriculture), flood metrics from flooding models as opposed to use of roughness metrics, and a formal treatment of adaptation and future land cover change through use of Natural Flood Management (NFM) and a development planning model constraining growth in areas of significant importance for biodiversity conservation. This would be expected to provide a better quantification of natural capital risk but is not expected to change the key message.

# 8. Agriculture

Climate change is projected to change both temperature and precipitation patterns in the UK, which would alter the climate suitability for growth of crop species in the UK, as well as altering the potential yields. This section reports on projected **changes in theoretical maximum yield (per hectare) of rainfed wheat and rainfed perennial rye grass**, which are the two most important crops grown in the UK by crop area and farm income (based on approaches in Brereton et al., 1996; Sylvester-Bradley and Kindred, 2014; and Lynch et al., 2017), and changes in the **potential range of 182 crops that could be grown** in the UK. The theoretical maximum yield (also known as potential yield) is always much greater than the actual observed yield because this assumes that many non-climate change related factors are ideal. The purpose of the model is to project the trend in yield and not the absolute values.

The wheat model reflects variations in sowing date, of water limitation, and heat stress. Perennial ryegrass (*Loilum perenne*) is the most common grass grown for agricultural production (hay, silage and grazing pasture) in the UK. Changes in yield are modelled and discussed below both with and without $CO_2$ fertilisation (the speeding up of photosynthesis because of higher $CO_2$ concentrations). Other factors that will affect crop yields and suitability such as potential changes in the spread of pests or diseases are not captured in the modelling. Limitations of the modelling are discussed at the end of the section.

**<u>Key messages</u>**

1. **Overall, UK mean potential wheat yields are projected to increase under the 1.5, 2, and 3°C warming scenarios (Figure 19), with evidence of levelling off under the 4°C scenario.**
2. **However, there are significant differences in yield response to climate across the regions, and the increases may be much smaller, or could be offset by other factors (see 3).**
3. **Realising such opportunities would require a large amount of adaptation to cope with spatial shifts in the most productive regions of the UK, changes in crop suitability, factors such increasing intensity and frequency of droughts, pests and diseases which are projected to increase in tandem with climate change.**

Under the 1.5°C warming scenario areas of south-eastern and eastern England suffer a modest reduction in wheat yield relative to baseline, especially on lighter soils (Figure 20). Yield for all other regions increases slightly. Under the 3°C warming scenario the relative yield reduction is greater in south-eastern and eastern England, whereas North-western and North-Eastern England and Eastern Scotland show a large increase in Wheat yield relative to the baseline.

These findings assume that $CO_2$ fertilisation will occur, and this may not be the case. The increases in wheat yield associated with the higher warming scenarios (3 and 4°C) for northern regions would be significantly reduced without $CO_2$ fertilisation (Figures 19, 21). Water limitation contributes to the levelling off of wheat yield at higher levels of warming.

4. **Under the 1.5°C warming scenario potential grass yields show modest increases (Figure 22) in all regions (Figure 23). Grass yields increase more markedly in all regions under the 3°C warming scenario with the greatest increases in the North-west (Figure 23).**

The increases in potential grass yield are significantly reduced without $CO_2$ fertilisation (figure 22, figure 24). There is also evidence of levelling off at the highest warming scenario (4°C).

4. **Crop suitability alters considerably for many crops, with larger changes for greater warming levels.**

With 1.5°C warming the temperature and precipitation become suitable for a greater range of crops to be grown in several regions (South-west and South-central England, South Wales, Northern Ireland, the North-east coastal fringe and Eastern Scotland), while for all other regions, a smaller range of crops show increases in suitability. These patterns become more pronounced under the 3°C warming scenario (Figure 25), with only regions in eastern England becoming less suitable. Identifying potential new crops as a pathways to increased climate resilience thus needs to consider crop types, spatial targeting and the ability of the local agricultural system to support the incorporation of new crops.

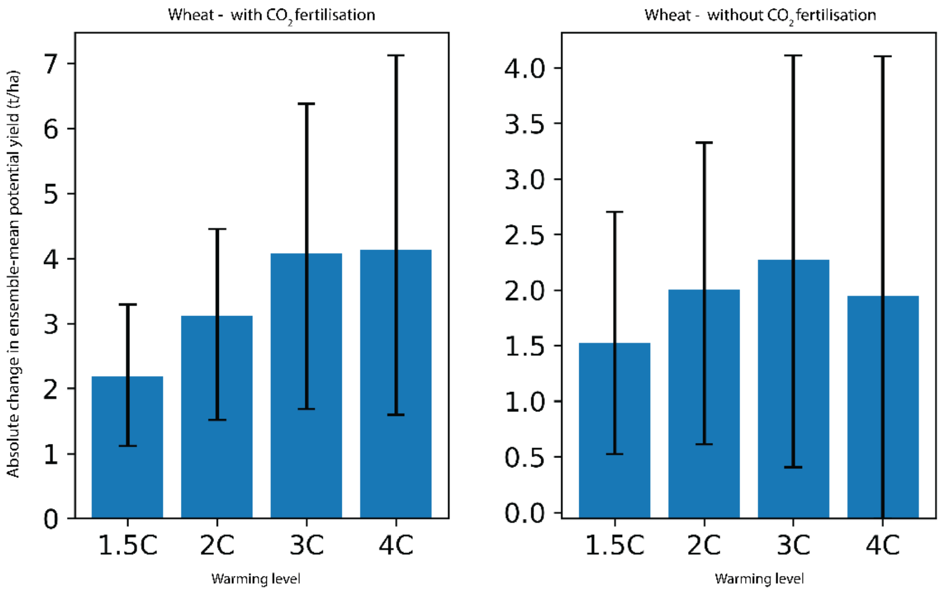


**Figure 19:** Left: Absolute change in ensemble-mean potential wheat yield (t/ha) over farmland for 1.5, 2, 3, 4°C relative to 1980-2010 simulated baseline of 11.8 t/ha. Left: with $CO_2$ fertilisation with errors bars showing range of model predictions from the ensembles tested. Right: without CO2 fertilisation relative to baseline with errors bars showing range of model predictions from the ensembles tested.

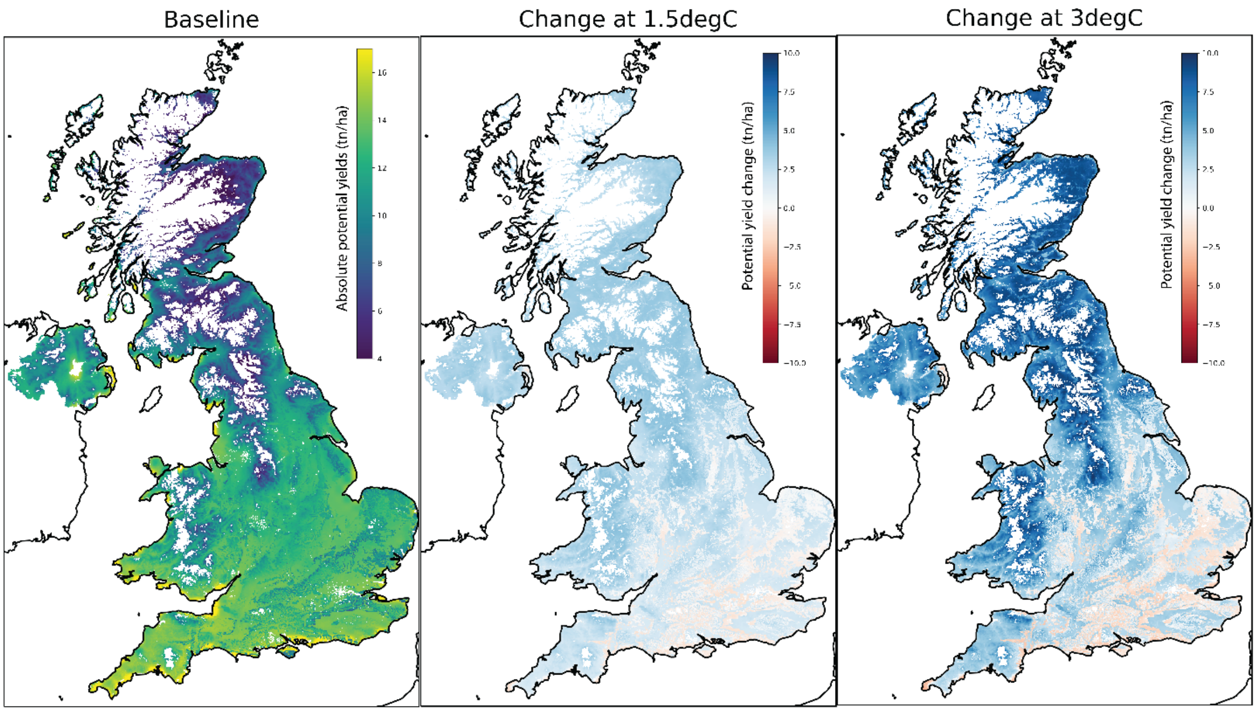


**Figure 20.** Absolute potential wheat yields for the baseline period. Change in ensemble-mean potential wheat yields with $CO_2$ fertilisation at 1.5°C and 3°C relative to 1980-2010 baseline.

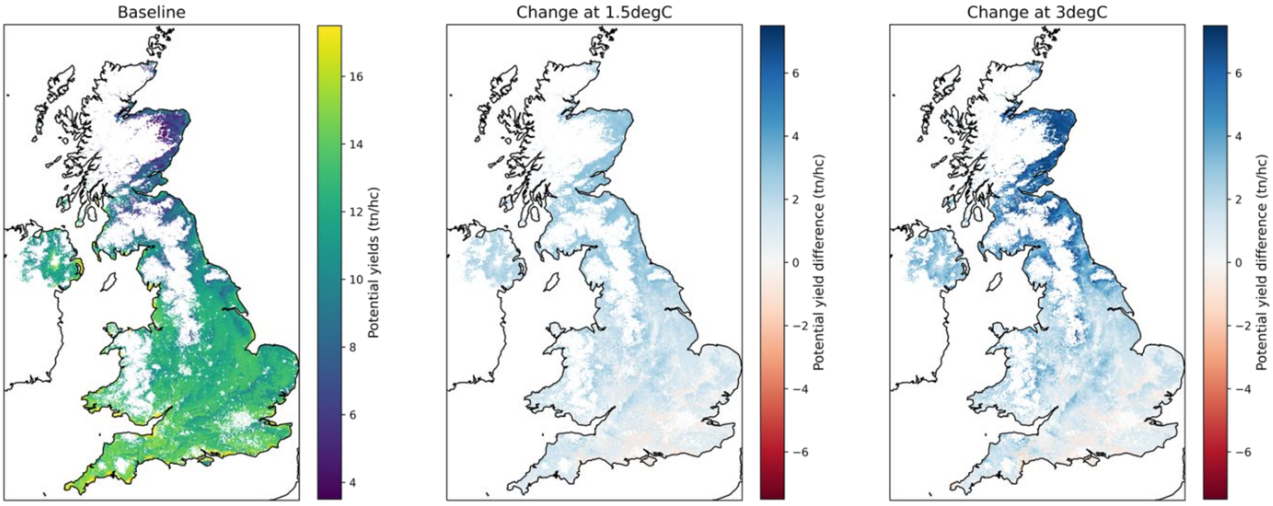


**Figure 21:** Absolute potential yields for the baseline period. Change in ensemble-mean potential wheat yields at 1.5C and 3C relative to 1980-2010 baseline without $CO_2$ fertilisation.

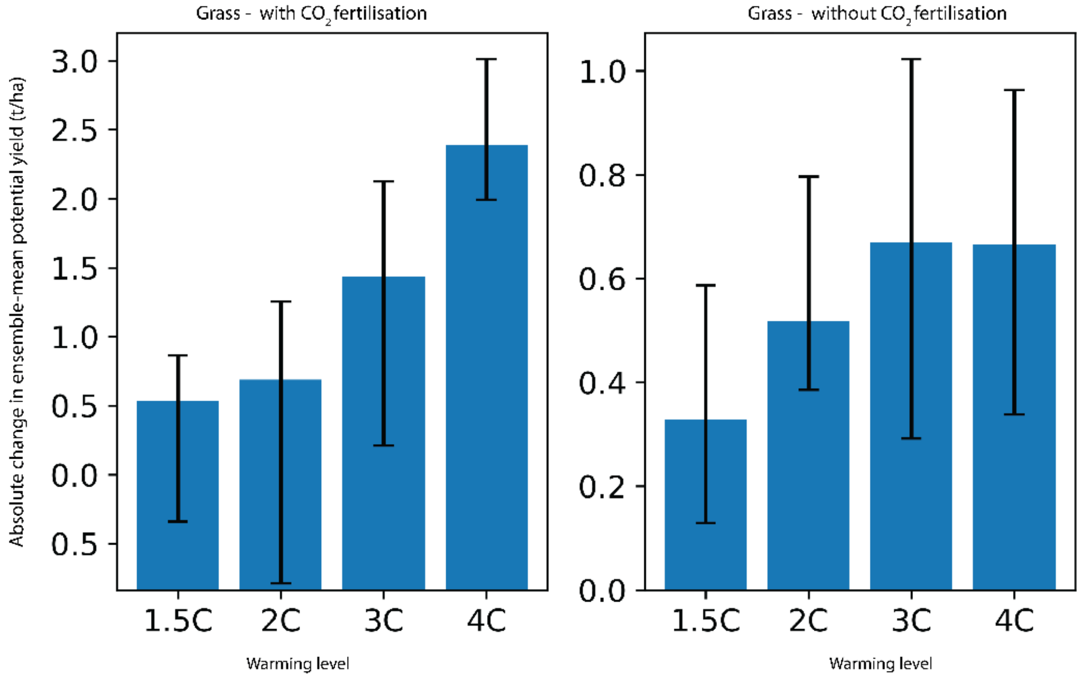


**Figure 22:** Left: Absolute change in ensemble-mean potential rye grass yield (t/ha) over farmland for 1.5C, 2C, 3C, 4C relative to the 1980-2010 simulated baseline of 6.45 t/ha. Left: with $CO_2$ fertilisation with errors bars showing range of model predictions from the ensembles tested. Right: Without $CO_2$ fertilisation with errors bars showing range of model predictions from the ensembles tested.

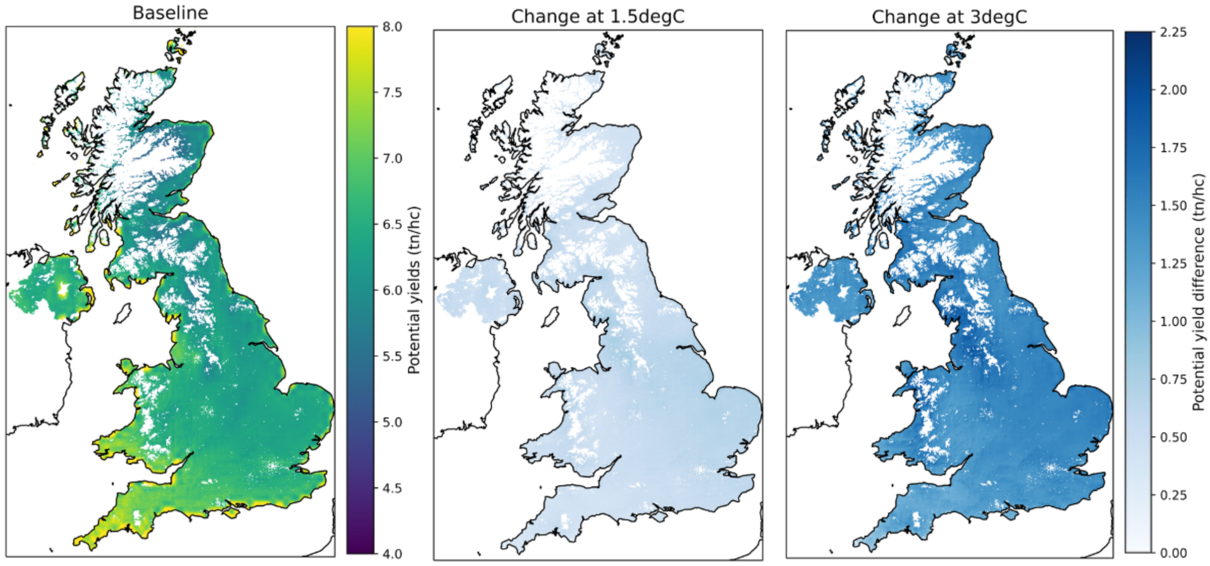


**Figure 23:** Absolute potential yields for the baseline period. Change in ensemble-mean potential rye grass yields with $CO_2$ fertilisation at 1.5C and 3C relative to 1980-2010 baseline.

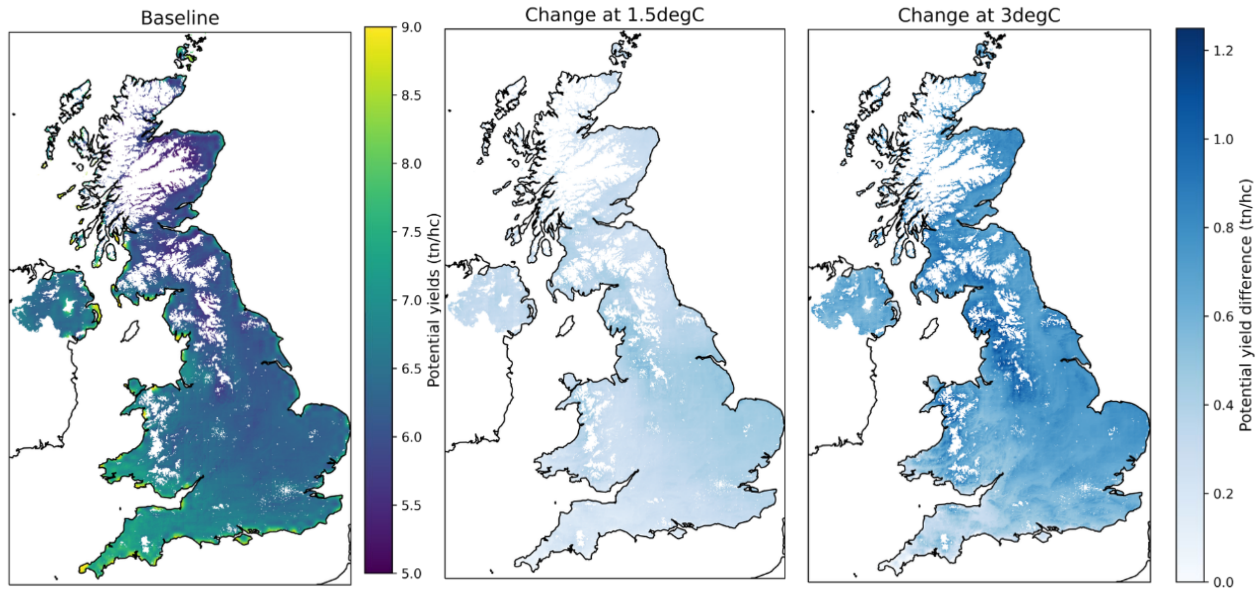


**Figure 24:** Absolute potential yields for the baseline period. Change in ensemble-mean potential rye grass yields without $CO_2$ fertilisation at 1.5C and 3C relative to 1980-2010 baseline.

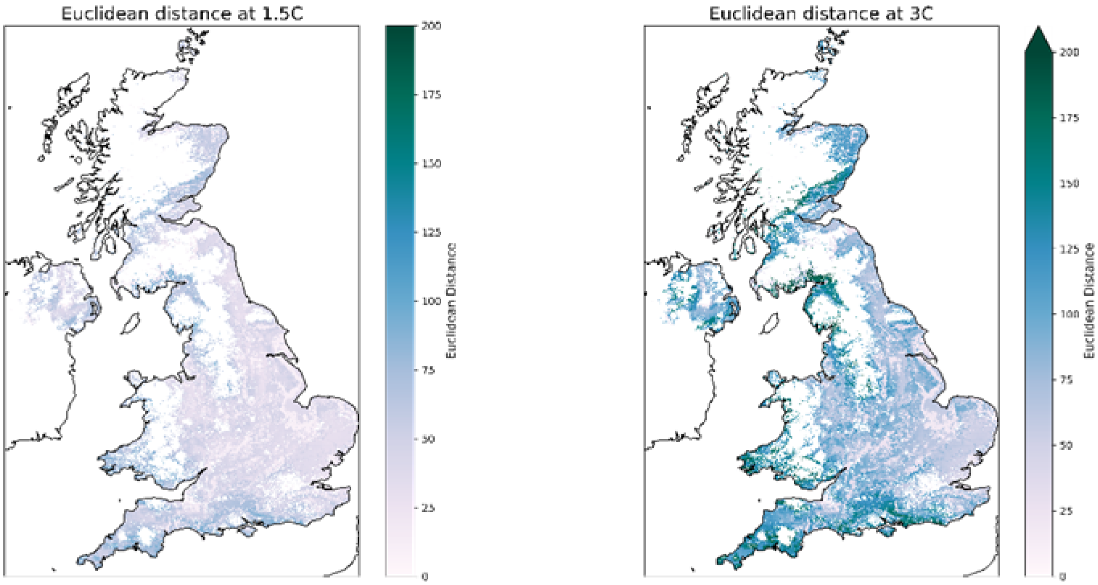


**Figure 25:** Change in the potential range of crops that can be grown (from the 182 crops modelled) under the 1.5 and 3C scenarios relative to the baseline period (1980-2010). Change is represented by calculating the Euclidean distance between the baseline and warming scenario for the temperature and precipitation suitability for each crop in each 1km grid cell and taking the mean of these distances.

## Caveats and limitations

Crop yield:

1. Models do not fully capture the potential effects of long term droughts (as opposed to short term drought) or floods and also assume no impact from non-climatic, agronomic parameters, such as crop nutrition, and pests or diseases.
2. The outputs of both models are only presented for areas currently suitable for growing arable crops and agriculturally improved grassland based on the UK CEH Land Cover Map 2021. Thus, upland and mountainous regions are excluded.
3. The outputs of the UKCEH CropNet Grass model are likely to be indicative of the maximum harvestable yield per year, as the model assumes that the grass is allowed to grow to senescence without periodic grazing or cutting.  Much greater climatic constraints may occur where climatic restriction on grass growth co-occur with the grazing needs of livestock.

Crop suitability:

5. Only temperature and precipitation are assessed, meaning that the suitability only reflects that for un-irrigated crops grown outside. Other impacts on suitability, such as changing soil characteristics, the spread of pests or diseases, or the availability of insect pollinators are not accounted for in this version of the model.

# 9. Agriculture and food security (water stress)

Both water resources availability and agricultural demand for water resources are likely to be affected by climate change, via perturbations of the hydrological cycle and the weather conditions in agricultural areas. The modelling presented here does not, however, include the additional effects of increasing populations or changes in diet that may affect water availability and the overall agricultural demand.

This section provides key messages on how changes in water resources supply and demand can affect water-risk for future food production. Two metrics related to food crops and water stress are presented for key UK staple crops (barley and wheat). The first metric is **crop water footprint (WF)**, representing the water demand by each agricultural crop in a given location over its growing season, which indicates how much water is required to grow a certain crop in a given year. The second metric is **crop virtual water content (VWC)**, representing the ratio of crop water footprint to crop yield. It indicates how much water is required to obtain a given amount of crop in a year (as opposed to being physically present in the crop after harvest) (Tuninetti et al., 2015). Both metrics are notably influenced by location and timing of planting, crop type, and climatic conditions. However, the model does not account for the effects of extreme weather events or $CO_2$ fertilisation which can also influence crop yield.

**<u>Key messages</u>**

1. **With global warming of 1.5°C, both positive and negative effects are seen on the crop water footprint (WF) and virtual water content (VWC) of barley and wheat across the UK.**

Negative effects are most apparent in South West England, shown by a larger percentage change in crop WF compared to the baseline (Figure 26). This reflects a localised increase in water needs, particularly localised for wheat.

2. **With global warming of 3°C, negative effects spread to most regions of the UK, showing an increase in water needs, with a notable spike in wheat water demand in Northern Ireland (Figure 27).**

These negative effects are consistent with the projection changes in yield reported in the previous section, where water limitation was found to contribute to yield declines at higher levels of warming.

3. **Barley's yield increases more than wheat with climate change, however in most regions of the UK, the change in crop water footprint is positive (Figure 26 and figure 27), indicating that the crop water demand increases faster than crop yield.**

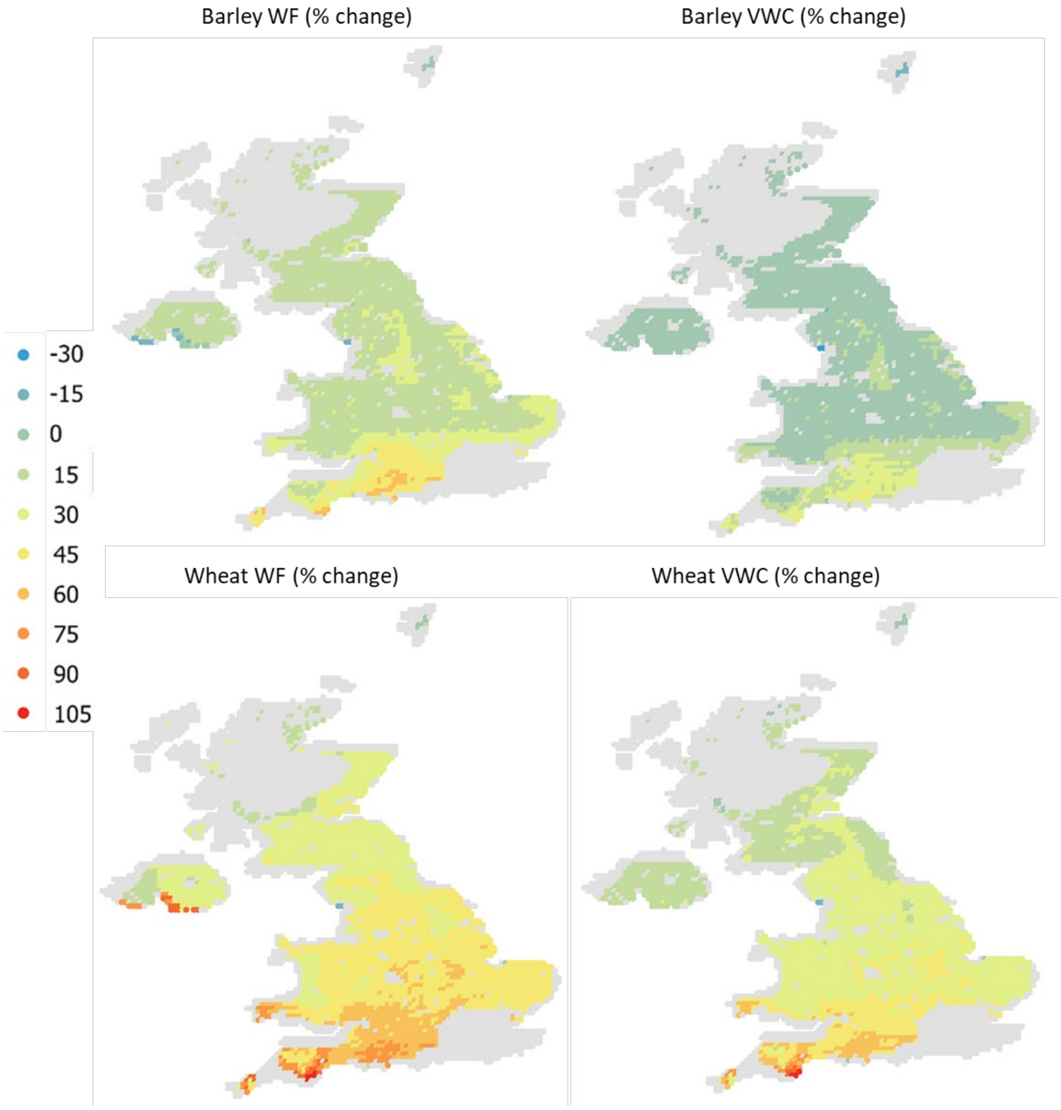


**Figure 26:** Change to baseline at 1.5°C: UK map showing for each crop (barley, wheat) and variable (VWC in m3/ton and WF in m3/yr) the % difference between 2025 values (this corresponds to 1.5°C of warming compared to pre-industrial levels) and 2012 values (1°C).

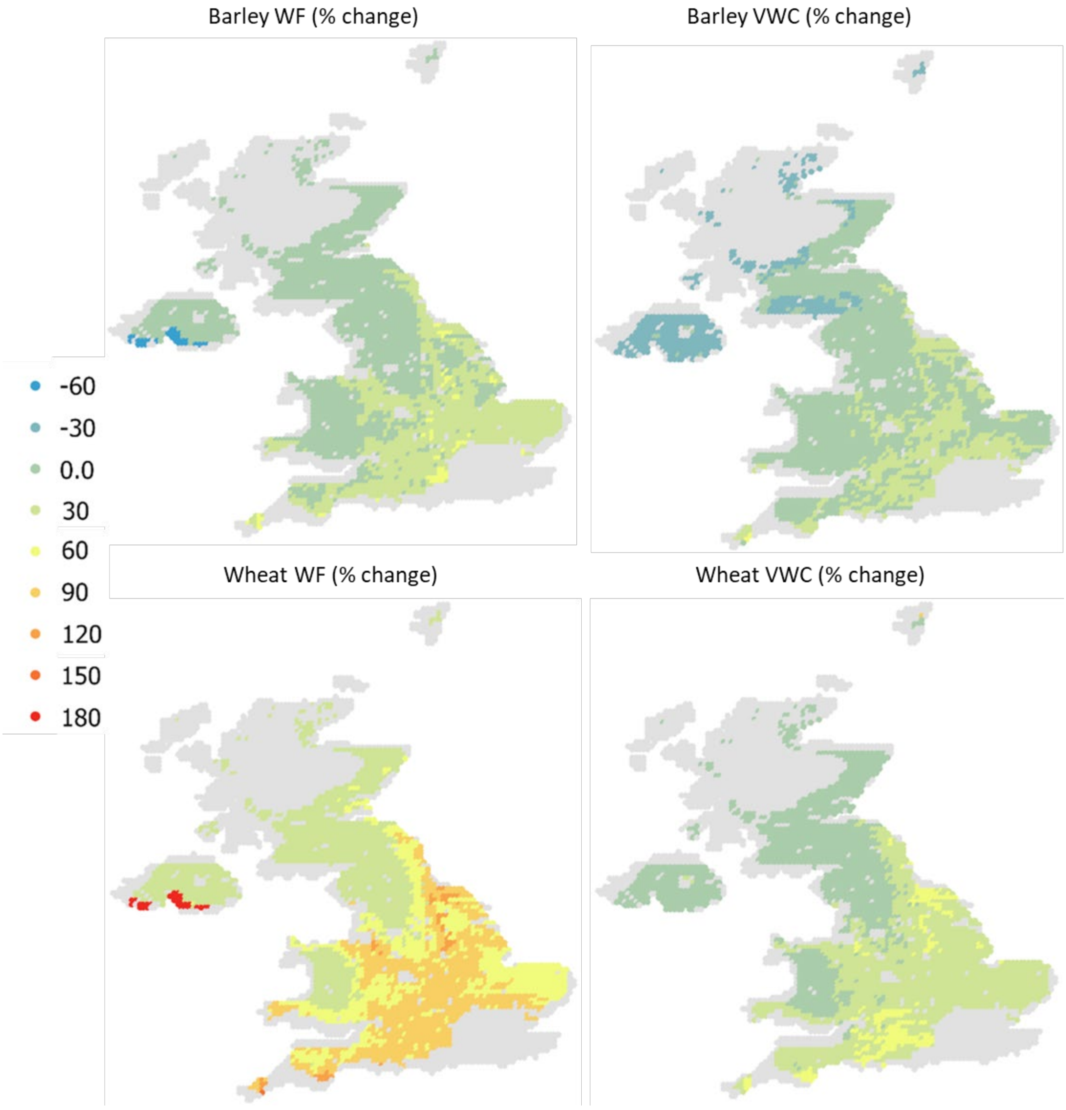


**Figure 27:** Change to baseline at 3°C: UK map showing for each crop (barley, wheat) and variable (VWC in m3/ton and WF in m3/yr) the % difference between 2056 values (this corresponds to 3°C of warming compared to pre-industrial levels) and 2012 values (1°C).

## Caveats and limitations

1. Crop yield projections were only available until 2°C. They are kept the same under the 3°C scenario, so that in the 3°C results, the crop yields are the same as those projected under 2°C, but the precipitation and evapotranspiration are projected under 3°C.
2. The crop yield projections are based on a statistical model (see appendix 12.2, section 9) which does not account for the effects of extreme weather events (expected to decrease yields) or $CO_2$ fertilisation (expected to increase yield).

# 10. Agriculture and food security (economic losses)

Climate change has already caused significant impacts on **global crop production**. Although regions are unevenly affected, most of them have experienced a decline in crop yields. It is expected that this trend will continue in the future. The projected impact of climate change without adaptation is generally negative even with the $CO_2$ fertilisation effect.

This section uses country estimates of crop yield changes at different local warming levels (1.5°C, 2°C, 3°C and 4°C) to assess the **economy-wide implications** of limiting global warming to lower versus higher temperatures in 2050 (see Appendix 12.2 section 10 for description of method and data). The use of local warming levels was necessary due to data limitations. These local warming levels over land can be converted to global warming levels using the estimated ratio of warming rates over land:ocean of 1.5 (IPCC AR6 Ch 4). Given that land occupies 29% of the earth's surface, IPCC average warming over land relative to the globe, hence corresponding global warming levels are approximately 1.2°C, 1.5°C, 2.3°C and 3°C respectively.

The UCL Environmental Global Applied General Equilibrium (ENGAGE) model is used to estimate the **economic impacts across sectors and across countries**, considering local conditions for agricultural production and adjustment processes in domestic and international markets induced by the direct impact of climate change and the indirect impact of changes in competitiveness.

**Key messages**

1. **In most regions, the expected decline in crop production is smaller than the decline in crop yield (figure 28).**

Climate change is expected to reduce crop yields and lower crop production. However, as farmers try to minimize their losses through efficient allocation of resources (such as land, labour, fertilisers) guided by changes in relative prices, the impacts on crop production become less than proportional. In some cases, such as cereals in Japan and rice in Mexico, production could even increase while yields decline. This is a result of the combination of the relative size of their crop impacts and the changes that these impacts cause to comparative advantages in food production.

2. **In most regions, climate change is expected to reduce crop yields and crop production. Higher warming levels results in even larger losses (figure 28).**

With the exception of wheat and the aggregated sector 'other crops' in regions with temperate climate and the boreal north such as Canada, the former Soviet Union and the UK, crop yields are expected to decline more with higher warming levels. Regions like Africa, India, Mexico and Australia may experience a 16-19% decline in wheat yields with a local warming of 4°C in 2050, corresponding to approximately 3°C of global warming. Wheat production in these regions declines between 10-23%, threatening regional food security.

3. **Limiting global temperature rise to 1.2°C in 2050 avoids larger global crop production losses and price increases versus higher warming levels (figure 29).**

In 2050 under SSP2, global crop production is reduced by 1-2% relative to a no climate change reference, translating to larger increases in global food prices of 4-7%. If regional warming were to reach 4°C in 2050 rather than 1.5°C (corresponding to global warming of 3°C rather than 1.2°C), additional global crop losses of 1.8-3.5% could occur. This translates to even larger increases in global food prices, an additional 8.5-9.9 percentage points depending on the crop. Climate change has a disproportional effect on vulnerable populations as it impacts both the physical and economic access to sufficient food to meet their dietary needs.

4. **GDP and welfare losses are small at the global scale; however, there are winners and losers at the regional level (figure 30).**

While the impact on Global GDP is small and positive for some warming levels, the impact on global welfare is negative and declines more with higher levels of warming. At the regional level there are winners and losers, although the impacts are also modest. Limiting global warming to 1.2°C in 2050 compared to 3°C in 2050 reduces regional economic losses from around 3% of the GDP to less than 1%.

**5. Regional GDP and welfare gains are expected in regions with temperate climate and in the boreal north (figure 31).**

Tropical regions such as Africa, India and 'Other Developing Asia' are adversely affected by climate change, whereas regions with temperate climates experience positive economic impacts—production, exports and welfare are projected to increase. China and Australia are exceptions—the changes in the terms of trade dominate the overall effect on welfare.

**6. Climate change generates new opportunity costs and modifies comparative advantages in food production (figure 31)**

In temperate regions such as Canada, the UK, Eastern Europe and Western Europe, the increase in exports is expected to be relatively larger than the increase in production. This means that these regions will not only produce more, but they will also export even more. The opposite is projected in regions where production is expected to decrease—exports decrease more than proportionally. As a result, trade patterns are projected to change. Farmers in regions where production increases may experience greater access to markets, while farmers in regions adversely affected by climate change may lose their market share, as they face lower yields and greater competition from elsewhere.

Actual changes in production, however, would depend on other factors besides economic demand. The ability to increase crop production depends on the availability of land, for which there are competing demands, and the effects of climate-change (see section 8 above) including long term drought, pests and disease which might reduce yields below the levels used as inputs to the ENGAGE model, including in temperate regions.

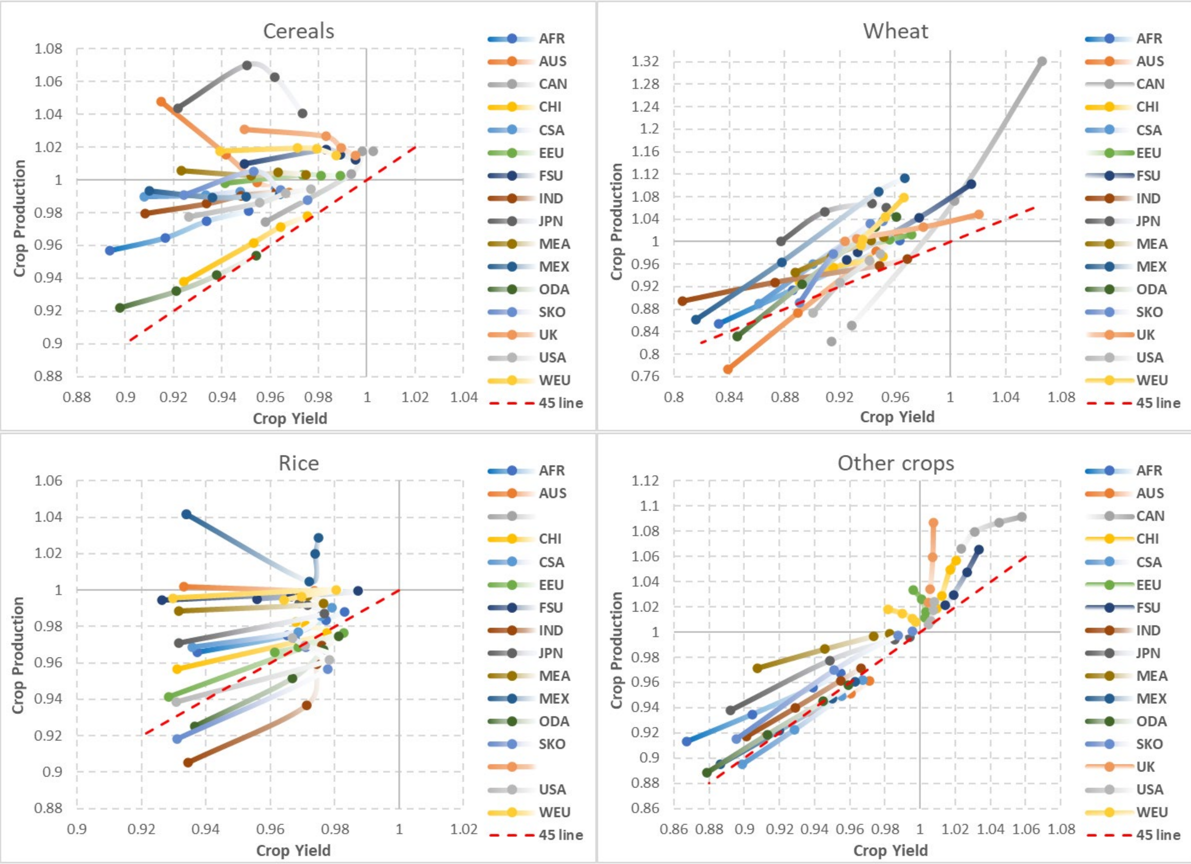


**Figure 28**: Relative change in regional crop yield and production in 2050 due to climate change at regional warming levels of 1.5 to 4˚C (corresponding approximately to global warming levels of 1.2 to 3˚C) (reference scenario with no climate change = 1). All scenarios use SSP2 assumptions. Each point represents a region and a warming level. The higher the warming level, the darker the line. The dotted red line represents a situation where the change in crop yield is directly proportional to the change in production. Maize yield changes are used for cereals and productivity changes for the whole agricultural sector are used for the aggregated sector ‘other crops’. Africa (AFR), Australia (AUS), Canada (CAN), China (CHI), Central and South America (CSA), Eastern Europe (EEU), Former Soviet Union (FSU), India (IND), Japan (JPN), Middle-east (MEA), Mexico (MEX), Other Developing Asia (ODA), South Korea (SKO), United Kingdom (UK), USA (USA) and Western Europe (WEU).

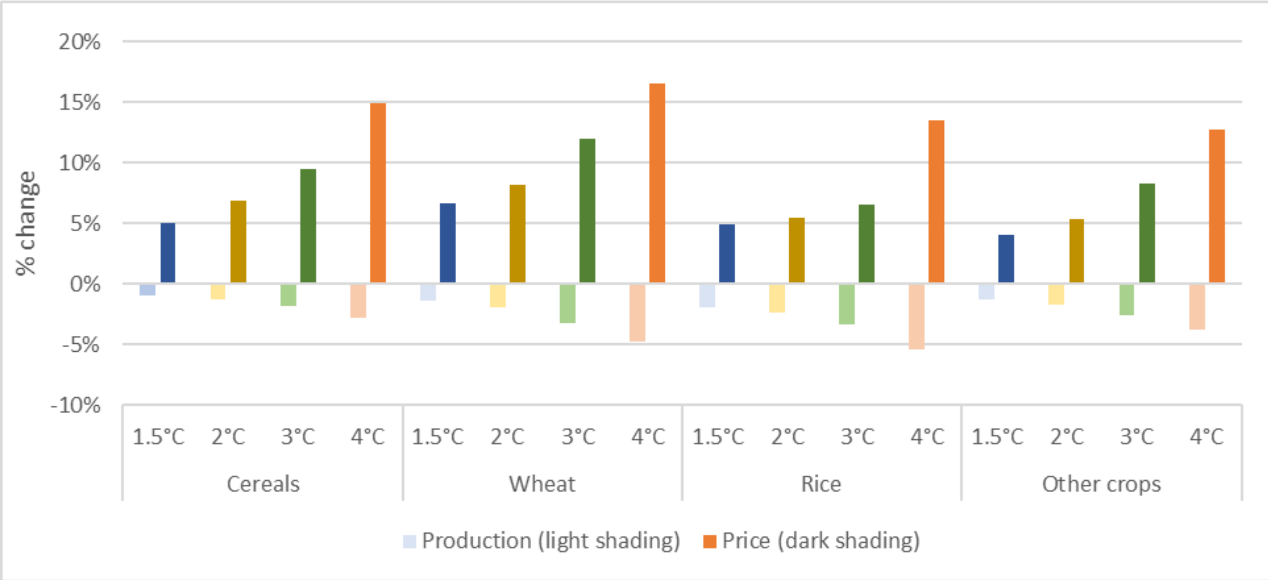


**Figure 29**: Change in global crop production and prices in 2050 due to climate change at regional warming levels of 1.5 to 4˚C (corresponding approximately to global warming levels of 1.2 to 3˚C) relative to a reference scenario with no climate change. All scenarios use SSP2 assumptions. Maize yield changes are used for cereals and productivity changes for the whole agricultural sector are used for the aggregated sector 'other crops'.

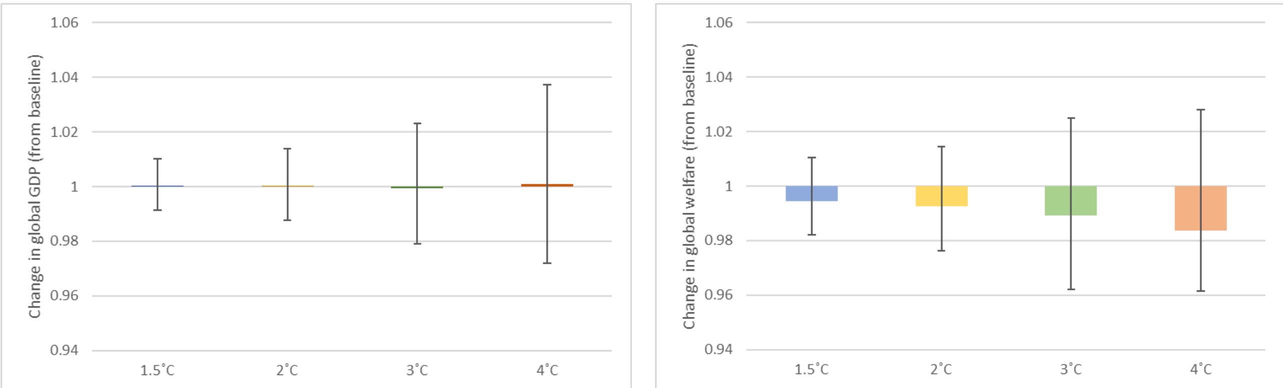


**Figure 30**: Relative changes in global GDP (left) and Welfare (right) in 2050 due to climate change at warming levels of 1.5 to 4˚C (corresponding approximately to global warming levels of 1.2 to 3˚C) (reference scenario with no climate change = 1). All scenarios use SSP2 assumptions. Errors bars show the range of regional changes in GDP and Welfare.

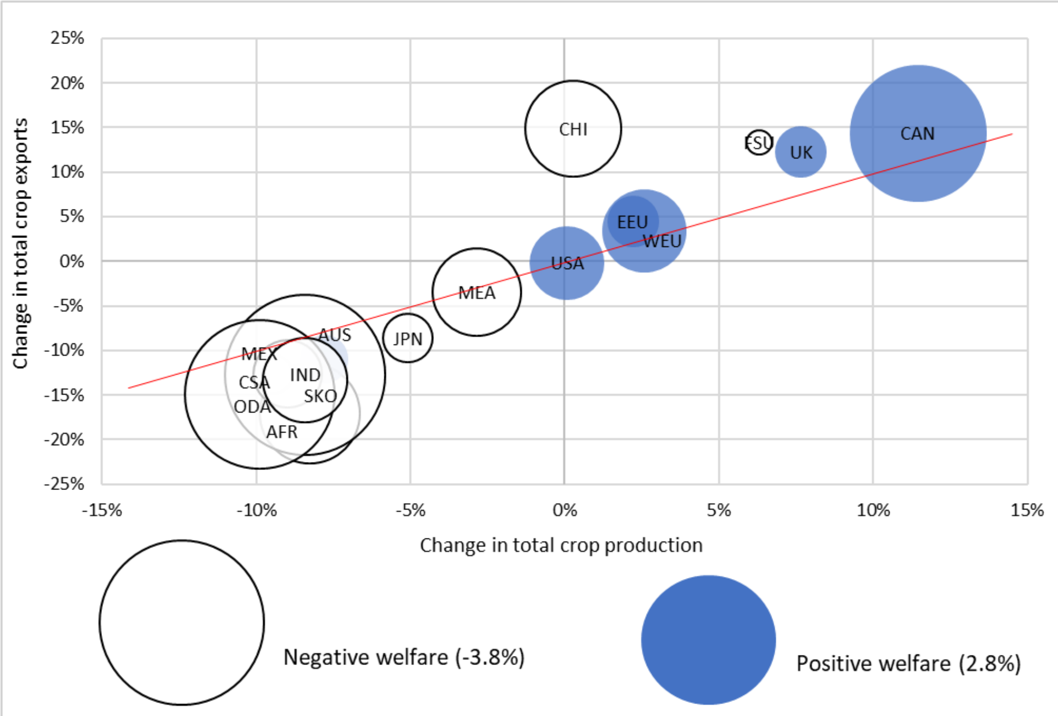


**Figure 31**: Changes in regional total crop production and exports in 2050 due to climate change at regional warming levels of 4˚C (corresponding approximately to global warming level of 3˚C) relative to a reference scenario with no climate change. Africa (AFR), Australia (AUS), Canada (CAN), China (CHI), Central and South America (CSA), Eastern Europe (EEU), Former Soviet Union (FSU), India (IND), Japan (JPN), Middle-east (MEA), Mexico (MEX), Other Developing Asia (ODA), South Korea (SKO), United Kingdom (UK), USA (USA) and Western Europe (WEU).

## Caveats and limitations

1. The model uses only one data source of crop yield changes to estimate the economic impact. The results are heavily influenced by this choice. The large uncertainty in crop yield -estimates should be captured by including results from different models and methodologies.
2. The crop yield changes used in this analysis are based on econometric estimations of damage functions. This database was selected as it gives impacts at different regional warming levels (from 1 to 5˚C). Other databases do not report impacts for local warming levels above 4˚C due to the low confidence of the results. The use of regional warming levels means that only an approximate correspondence to global warming levels as possible. It was necessary to link the local and global warming levels, and in doing so it was necessary to make the incorrect assumption that local warming of 3˚C over land uniformly corresponds to a global warming of 4˚C. This approximation means that in some regions, impacts might be larger or smaller than indicated.
3. The damage functions use local temperature changes to estimate crop yield changes. This implies that all regions experience the same warming level, which is inaccurate. In addition, since land warms faster than oceans, the global temperature change is expected to be lower than the assumed local temperature change.
4. Maize yields were used as a proxy to estimate the climate change impacts on the cereals sector in ENGAGE which includes maize, sorghum, barley, rye, oats, millets and other cereals. As the share of maize production in tonnes represents more than 80% of the whole cereals sector, this assumption seems acceptable.

5. Productivity changes for the whole agricultural sector were used as a proxy to estimate the climate change impacts on the ‘other crops’ sector in ENGAGE. As the ‘other crops’ sector in ENGAGE includes vegetables, fruits, oil seeds, sugar crops, fibre crops and other crops not classified elsewhere, this assumption seems acceptable.
6. Similar to most global economic models, the ENGAGE model includes highly aggregated sectors and regions. While it accounts for regional differences in crop yield changes, local effects within these regions are averaged out.
7. We do not assess uncertainties within the economic model. A sensitivity analysis in key parameters and elasticities might provide further insights.
8. The model assumes that crop production will increase if a demand exists. In practice this will depend on other factors such as the availability of land.

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# 12. Appendix

## 12.1 IPCC Definitions

Table 12.1: IPCC terms and definitions.

| Term | IPCC AR5 (Oppenheimer, Campos, Warren et al. 2014) | IPCC AR6 (in press) |
|---|---|---|
| Hazard | The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. | As AR5 |
| Vulnerability | The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. | As AR5 |
| Exposure | The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected. | As AR5 |
| Risk | The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability or likelihood of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. In this report, the term risk is often used to refer to the potential, when the outcome is uncertain, for adverse consequences on lives, livelihoods, health, ecosystems and species, economic, social and cultural assets, services (including environmental services) and infrastructure. | The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and wellbeing, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.<br>In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. Hazards, exposure and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence, and each may change over time and space due to socio-economic changes and human decision-making. |
| Adaptation | The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or | In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In |

| Term | IPCC AR5 (Oppenheimer, Campos, Warren et al. 2014) | IPCC AR6 (in press) |
|---|---|---|
| | avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects. | natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects. |
| Sensitivity | | The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise). |

## 12.2 Models, methods and data

**Section 2 – High temperatures and health**

HARM uses a threshold-based approach to calculate exposure. Regional Linear Exposure-Response Functions (ERFs) define heat thresholds above which daily mortality will increase by a given percentage. The ERFs are based on statistical associations between daily mean temperature and epidemiologic data on mortality (described in full in Jenkins et al., 2022).

The model provides spatially explicit projections, using the latest UKCP18 regional 12 km data and incorporates socio-economic data (population, demographics, residential building numbers/type) using the UK-SSPs 2 and 4 to reflect the exposed population and vulnerability to heat via demographic data and relationships between age and Relative-Risk (RR) values provided by the linear ERFs.

Climate data is based on the UK Met Office's UKCP18 twelve-member regional climate model (RCM) ensemble at 12 km resolution. The data was bias corrected using ERA5 reanalysis following the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) 2b bias correction method, as applied in Kennedy-Asser et al. (2021). For each global warming level, climate variables for each 30-year period, representative of the different levels of global warming above pre-industrial temperatures, are extracted. The 30-year time periods for each global warming level were based on start and end years published in Arnell et al. (2021), with the exact years for each global warming level varying slightly between UKCP18 RCM simulations (Kennedy Asser et al., 2022). UKCP18 RCM simulations follow CMIP5 historical climate forcing until 2005 then representative concentration pathway 8.5 (RCP8.5) until 2080. Baseline: 1981-2000.

**Section 3 – Hydrological drought**

Hydrological droughts are identified using the threshold level method with the standardisation method previously developed by Rudd et al. (2017, 2019) for use with G2G model output (Kay et al., 2022). This procedure, summarised below, is applied to a time-series of G2G-simulated monthly mean river flow to identify droughts, and their characteristics.

The drought identification and characterisation procedure is as follows: A drought event is assumed to start when the river flow falls below a threshold and continues until the threshold is exceeded again. Here the threshold is the long-term mean monthly flow from Jan 1989 - Dec 2018 (baseline period: 1989-2018), thus removing the seasonality in hydrological response. The procedure is as follows:

Step 1: Remove the long-term monthly mean flow, Xmon (1989-2018) from the monthly mean time series, X.

anomaly = X - Xmon

Step 2: Where the anomaly is negative (i.e., a deficit) calculate the duration, intensity and severity of that deficit.

i) drought intensity — the deficit (m3s-1);
ii) drought duration — the length of time in deficit (months); and
iii) drought severity — duration multiplied by mean drought intensity.

To allow comparison of drought characteristics for different locations the time series of flow “anomalies” can be standardised by dividing by the standard deviation of mean monthly flow, σmon, also from the years 1989-2018. Thus a “drought” is defined as the period of time for which the variable is below normal, i.e., a deficit.

Step 3: Repeat steps 1 and 2 for the standardised anomaly by dividing by the long-term monthly standard deviation (1989-2018)

standardised anomaly = (X - Xmon)/σmon

Step 4: Select only the deficits where the standardised severity is greater than or equal to the severity thresholds used in Rudd et al 2017 and 2019. For the Department for Energy Security and Net Zero CS-N0W project we use the moderate-threshold.

**Section 4 – Flood risk**

The use of alternative pathways for the rise in Global Mean Surface Temperature (GMST) influences each flood hazard in a different way. In the case of changes in fluvial flows and rainfall, for example, it can be assumed that the change is conditional on the GMST alone and not the pathway of the rise (a reasonable assumption, James et al, 2017 and the assumption made in CCRA3, Sayers et al, 2020). Sea level rise (and hence coastal flooding) is however conditional on both the rise in GMST and time to that rise (reflecting the significant inertia in the response). To account for the pathway of the rise, the SLR projections used in support of the CCRA3 analysis are modified using insights from a multiple model comparison of how global sea levels may be influence by an accelerated rise in GMST (Jevrejan et al., 2018, Jackson et al., 2018) and further analysis of the UKCP18 outputs (Matt Palmer and Jason Lowe, personal communication, March 2023).

**Section 5 – Terrestrial biodiversity**

The global analysis reported in Warren et al (2013, 2018a) is based on the Wallace Initiative database and contains projections of potential climate change impacts on the climatically determined geographic ranges of more than 130,000 individual terrestrial species. This study uses the most up to date version of this database to extract projections of the impacts of climate change upon plants and vertebrates in the UK, at alternative levels of global warming (specific warming levels, SWLs) of 1.5, 2, 2.7, 3.2, and 4.5°C (as well as 6°). For consistency with other projects, we have subsequently interpolated linearly between simulations in the database in order to extract projections matching SWLs of 0.5°C to 4.5°C of warming in 0.5°C increments.

The data found in the Wallace Initiative database has been widely used in the studies published in peer-reviewed journals (e.g., Jenkins et al., 2021; Manes et al., 2022; Price, et al., in revision a; Saunders, et al., 2023; Smith, et al., 2018; and Warren et al. 2013, 2018a, 2018b). The results from the Wallace Initiative database should be viewed as a statistical sample to attempt to discover the underlying relationships, trends and patterns for broader populations. To that end, extensive resampling and testing have been done to assess how well it performs in terms of general trends and patterns. Results have been found to be generally robust to choice of climate model - CMIP3 vs CMIP5 (current) vs. high resolution RCM models (EU project Helix).

The methodology follows that used in Warren et al. 2018 (a,b) and Warren et al. 2013. The global scale Wallace Initiative (WI) database was created using an established species distribution model, MaxENT, to estimate potential changes to the ranges of more than 130,000 terrestrial fungi, plants, invertebrate and vertebrate species associated with levels of global warming between 1.5 and 6°C (relative to pre-industrial levels), using 21 alternative regional climate change projections for each level of warming to incorporate uncertainty in regional climate projection, derived from the CMIP5 model inter-comparison project. As in Warren et al (2018a,b) calculations were carried out at a 20x20 km scale. The MaxENT analysis relies on developing a statistical relationship between current species distributions and current climate, and assuming this relationship holds into the future. To develop these models, species distribution data for a large number of species is required and this was sourced via the Global Biodiversity Information Facility (GBIF).

While the original Wallace Initiative database was modelled at a spatial resolution of approximately 20km x 20km, these data have subsequently been ‘elevationally’ downscaled to 1km x 1km following the methodology outlined in Price et al., in revision and Saunders et al., 2023. To match land cover maps these data were then resampled (ArcGIS Pro, RESAMPLE, nearest neighbour) to match the subsequently used land cover data - either 300mx300m (ESA-CCI), or 20mx20m (CEH, used in OpenCLIM).

This particular study relies on mining the existing Wallace Initiative database that projects changes in species climatic distributions. A complete consideration of the caveats of the modelling process can be found in Price, et al. (in revision) and Warren, et al. (2013, 2018a, 2018b).

**Additional analysis on Dispersal, pioneers and colonizers**

Figure 12.1 below shows the difference considering dispersal makes to changes in species richness remaining. Most groups of species have low dispersal rates, too low to adequately pick up at the scale of resolution of the original models (20km, see Warren et al. 2013 for more details). Even among those animals with higher dispersal rates it is only the flying species (e.g., birds, butterflies, moths, dragonflies, some bees, and bats) that may have the opportunity of pioneering into the UK from Europe. However, while many of these species can travel long distances, they may not readily cross the English Channel. This is not unique to the UK; it is an aspect of island biogeography around the globe. It is important to bear in mind that while dispersal benefits the species (in terms of lowering extinction risk (Warren et al., 2018) it may be detrimental to the ecological communities. These communities face losing species and their ecosystem services (e.g., pollination and seed dispersal) with some percentage of new species coming in that may not be able to replace the lost services. In higher elevations and more northern latitudes there may be an overall increase in species, but the new species may be in competition with the existing species over food or breeding habitats. The consequences of these community transformation are largely unknown, and this could easily lead to ‘surprises’ (Burkett et al. 2005). The overall low percentage of change is a function of the species able to disperse relative to the overall number of species (most of which have much smaller dispersal rates). Thus, the number of potential colonists from Europe in southern England is <4% in the models, even at 3°C.

It is true that among some groups of species (e.g., birds) there will be more pioneers. This can be tricky to accurately calculate as many models project that the climate is already suitable in the UK for the species (e.g., European Bee-eater, Red-backed Shrike), but that barriers may be preventing their colonization. In other instances, the species were here in low numbers but have been undergoing population increases (e.g., Little Egret, European Spoonbill). An analysis was performed for Norfolk on which species may occur with increases probability coupled with those species potentially lost (Price, 2019). In this paper, 15 bird species were projected to lose their climatic range within Norfolk, while 27 are projected to increase in likelihood of occurrence. However, of these 27, 8 are/were in Norfolk already, 5 have recently occurred with likely breeding, so only 14 are still occurring only as a regular or rare vagrant (or not at all). For butterflies it is 11 species losing climate suitability with no projected pioneers, and this repeats for macro moths (several hundred losing climate suitability), bees, and dragonflies.

Price, J. 2019. The potential impacts of climate change on the biodiversity of Norfolk. *Trans. Norfolk Norwich Nat. Soc* 50(1).

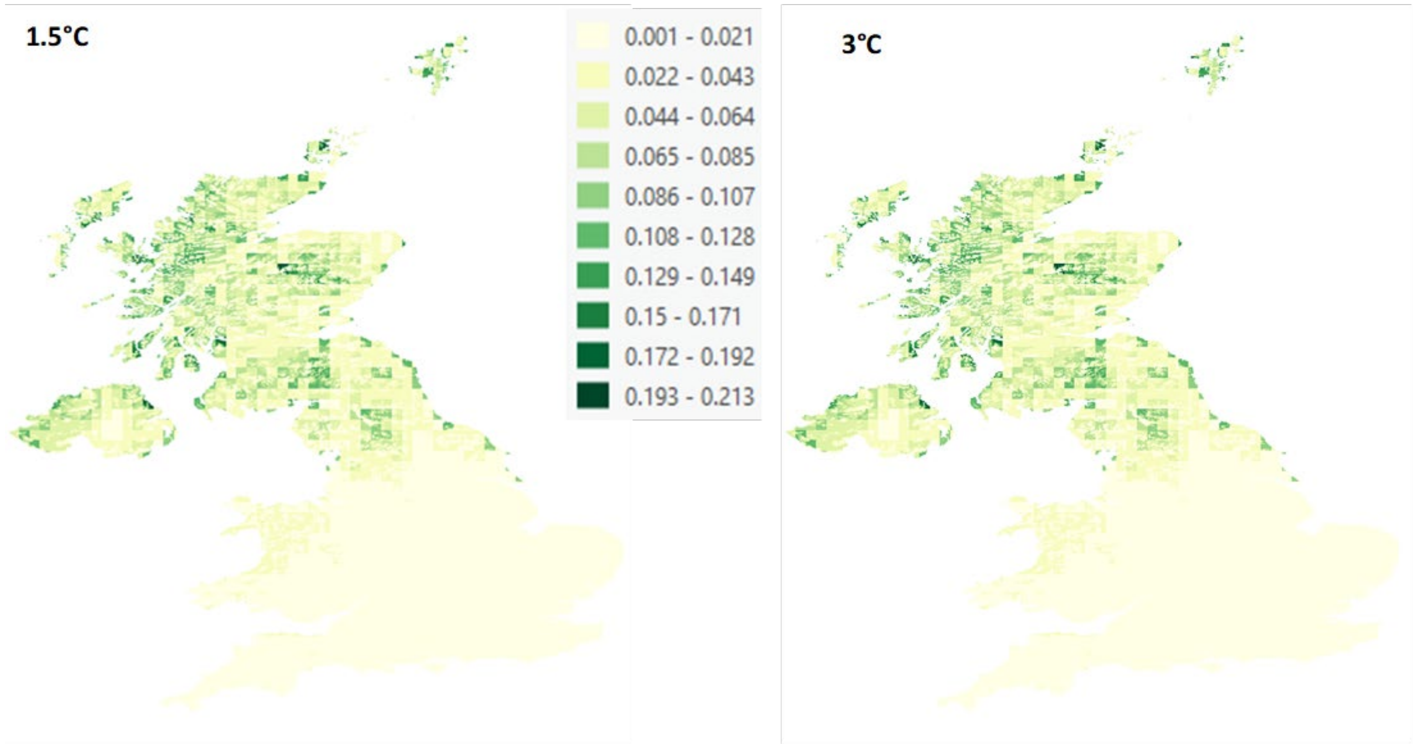


Figure 12.1. Difference in How Dispersal in Animals (either in latitude (including from Europe) or altitude) Affects the Number of Species Remaining in Animals (including insects). These maps for 1.5° (left) and 3°C (right) were calculated by subtracting the original species richness remaining maps (no dispersal) from those with dispersal. The difference is the change in species richness from no dispersal to with dispersal. In the southern UK, there is little difference (<2%) at 1.5°C and <4% at 3°C in a few places on the Norfolk coast. Most of the changes are at higher elevations and latitudes.

**Section 6 – Marine environment (Fisheries)**

The first and main metric is the ***fish abundance***; that is the abundance of fish within the UK EEZ. This can be looked at as a temporal or spatial metric. Looking at as a temporal metric shows the mean abundance of fish in UK EEZ water and whether it will decrease or increase under climate change. If used as a spatial metric it also shows us the second metric ***fish distribution***; that is the areas where there are higher concentration of fish.

The Size Spectrum – Dynamic Bioclimate Envelope Model (SS-DBEM) is a species-specific model that resolves both habitat preferences and population dynamics based on available food in the system (Cheung et 2009, Fernandes et al 2013, Wilson et al., 2021). The SS-DBEM uses several input variables (temperature, salinity, primary production, oxygen, pH and currents) to evaluate habitat suitability, system carrying capacity, and population growth. These input variables are obtained from a physical-biogeochemical model of the marine ecosystem, in this case ERSEM (Kay, S, 2020, Galli et al., 2020, Sailley et al., 2020), which in turns correspond to the climate forcing and respective warming scenario. Fishing pressure is added as a multiple of the Maximum Sustainable Yield (MSY, that is the amount of fish that can be removed from the system without causing the fish population to be over-exploited). That fraction of the MSY is chosen to match current or expected fishing levels, or can be used to create an explorative scenario looking at the combined impact of climate change and fishing (Wilson et al., 2021).

The model is run for the whole Northeast Atlantic shelf, according to the domains of the forcing model, we then extracted the data that correspond to the UK EEZ for the spatial range of the analysis. Maps present the spatial change averaged over a period of time or for a specific year, while plots show the annual change averaged over the whole of the UK EEZ.

The climate forcing was one aspect of the runs used to assess impact of climate change on fisheries, the second one being fishing. This was done to assess the impact of socio-economic decisions in combination with climate change impact. If desired each combination of climate and fishing scenarios can be paired to an equivalent SSP:

- SSP2: RCP4.5 with fish stock is managed globally toward sustainability by limiting catch to 60% of MSY
- SSP3: RCP8.5 with fish stock is managed globally to avoid overfishing by limiting catch to 80% of MSY
- SSP5: RCP8.5 with fish stocks managed nationally without cross consultation resulting in overfishing, fishing exceeding the MSY by 10%

Two time periods were examined: mid-century (2050) and end-century (2080-2100). Respectively, with RCP4.5 and RCP8.5 this correspond to the following levels of global warming:

- Mid-century: 2.1+/-0.3C and 2.6+/-0.4C above pre-industrial mid century
- End-century: 2.5+/-0.5C and 4.3+/-0.7C end-century respectively (Table 12.2, IPCC AR5, WGI)

**Section 7 – Natural capital**

Biodiversity underpins ecosystem services and natural capital is biodiversity. The biodiversity components used in this metric of natural capital are mainly species richness (and concomitant change) across a range of taxa. The exceptions are stewardship (protected areas (IUCN 2018) with natural land cover); carbon (aboveground and belowground biomass to estimate carbon storage (Soto-Navarro et al. submitted), normalised against a set value); and food (uses the Standardised Precipitation Evapotranspiration Index (SPEI) to look at the potential impacts of drought and/or waterlogging on agriculture)

The analysis begins with an assessment of how present-day land use and population constrains ecosystem services and hence natural capital. The additional stresses of climate change and population growth are then simulated. As this is based on the biodiversity analysis, the same climate data are used as noted in section 5 above.

Each of the 17 ecosystem services were scaled from 0 (none remaining) to 1 (full potential remaining). The full list of the 17 ecosystem services and what they are composed of can be found in Price et al. (b), in review. The ecological footprint used is approximately 4.2 (a sustainable value is considered to be 1.7).

**Section 8 – Agriculture**

The UK Centre for Ecology & Hydrology (UKCEH) CropNet Wheat and CropNet Grass yield models simulate ‘potential’ yield of wheat and grass (Perennial ryegrass) growing under rainfed conditions in the UK, based on key meteorological inputs (solar radiation, temperature and precipitation). The models account for climatic variables, soil effects on water availability, and day length. The models run at daily timesteps and output annual yield per hectare (t/ha). The models have been designed and calibrated to produce estimates of crop yield impacts over relatively large spatial extents and long timescales (i.e., climate change impacts on patterns of yield across the UK).

The UKCEH CropNet Wheat model is based on approaches for simulating potential yield developed by Sylvester-Bradley and Kindred (2014) and Lynch et al. (2017), and also accounts for the impacts of variation in sowing date, of water limitation, direct heat stress and $CO_2$ fertilisation. The model has three main stages: i) estimation of the green area index (GAI) over the growing season; ii) convert this time series of GAI into biomass via an estimation of solar radiation intercepted by a wheat plant with given GAI. Water limitation is applied to the biomass conversion based on the rainfall and available soil water; iii) convert the biomass to grain yield and apply a waterlogging penalty based on the rainfall and water capacity of the soil. Patterns of predicted Wheat yields for the baseline period (1980-2010) are confirmed by Defra Wheat yield statistics. The difference between achieved and potential predicted yields appears to be consistent and represent yield loss due to factors such as pests and diseases, soil degradation and suboptimal agronomic decisions.

The UKCEH CropNet Grass model is based on that of Brereton et al. (1996). It uses a parameterised relationship between daily temperature and the efficiency of the conversion of solar radiation to biomass to calculate the biomass accumulated each day. This is water-limited by calculating the ratio of actual to potential evapotranspiration, the former calculated using the soil moisture deficit derived from precipitation and rainfall, and the latter using the standard Penman-Monteith formulation. The yield is the sum of the water-limited biomass produced each day.

The crop suitability metric shows the relative climatic suitability (temperature and precipitation) of each 1km grid cell in the UK for 182 annual and perennial crop species under different levels of warming. The UKCEH EcoCrop crop suitability model runs at a daily timestep and derives a suitability score based on daily temperature and daily precipitation using required and optimal temperature and precipitation ranges, and the range of the number of days within which the crop must grow (GMIN to GMAX). The temperature suitability score for a given crop is based on the average temperature and how this relates to the crop's required and optimum temperature ranges. The average score is calculated for a series of growing times between GMIN and GMAX, and the maximum taken as the final score. The precipitation suitability score is calculated in a similar way but summing the precipitation rather than calculating its average. The scores are calculated in a forward-rolling manner from each day, and then aggregated into yearly scores.

## Section 9 – Food security and water stress

Methods for crops' Water Footprint (WF) and Virtual Water Content (VWC) follow Tuninetti et al (2015) and Bonetti et al. 2022 and are described here. WVC is defined for each grid cell as the ratio between the water evapotranspired by the crop during the growing seasons of a year and the actual crop yield. Daily crop evapotranspiration is calculated following Allen et al. (1998). The reference evapotranspiration (i.e., potential evapotranspiration) is obtained from the ISIMIP database using the ORCHIDEE land surface model and HAdGEM2-ES climate model under RCP8.5. This potential ET is based on climatic variables including temperature, air humidity and wind speed.

To calculate crop yield projections the methodology used in this study involves two steps: i) estimating the coefficients related to the selected model for each crop using historical data (1986-2012), and ii) forecasting the crops' yield based on the estimated coefficients in step 1 and climate scenario (temperature and precipitation based on RCP 2.6 with the HadGEM2-ES model - corresponding degrees of warming: 2012: 1 degree C; 2026: 1.5 degree C) for years between 2013 and 2050.

The main model includes a country-specific quadratic trend, an individual-specific time-invariant component, a common time-variant component, and a set of observed variables potentially affecting crop yield, which include temperature, precipitation, pesticides, fertilisers, and an indication of the degree to which irrigation is utilised in the agricultural sector. In the second step, using the estimated coefficients and weather scenario (RCP 2.6) inputs, we forecast the crops' yield for the years between 2013 and 2100.

To adjust the forecasted results, we first calculate the difference between the fitted and observed values for the years between 2007 and 2012. Then we compute the average value of these differences for each crop at the country level and add this average difference to the forecasted values. Furthermore, to consider the potential yield of the crops in each country, we set a plateau to generate more realistic and feasible projections using the potential yield as a cap that is increased by 5% per decade.

While the WF metric is based on gridded projections for all levels of global warming until 3 ºC, the VWC metric (i.e. WF/Y where Y is crop yield) is based on coarser Y projections for the 2 ºC and 3 ºC global warming levels. Gridded crop yield projections were only available until the 1.5ºC global warming level. However, crop yields were also projected at country scale in the RCP 6.0 scenario with HadHGEM2-ES, and we found that UK wheat yield under 2ºC was not significantly different than under 1.5ºC. For barley, we use the yield trend at national scale between 1.5 and 2 ºC to extrapolate the gridded yield at 1.5 to 2 ºC. Barley and wheat yields are then kept constant between the 2 and 3 ºC levels.

## Section 10 – Food security and economic losses

Estimates of crop yield changes at different regional warming levels are based on the World Bank Policy Research Working Paper "Estimation of climate change damage functions for 140 regions in the GTAP9 database" (Roson and Sartori, 2016). Crop yield changes for maize, wheat and rice are estimated based on a meta-analysis provided in the Fifth IPCC Assessment Report (2014), considering central values of the percentage simulated yield change (without adaptation) as a function of local temperature change and associating the type of region (temperate or tropical) to its latitude (Roson and Sartori 2010). The productivity change for the whole agricultural sector is estimated based on reduced forms of agricultural response functions where the variation in output per hectare is expressed as a function of temperature, precipitation P and $CO_2$ concentration (Mendelsohn and Schlesinger 1999). These crop yield changes do not account for the potential impacts of extreme weather events, pests and diseases, and farmers' adaptions.

Wheat and rice yield changes are used directly in ENGAGE, whereas maize yield changes are used as a proxy for the aggregated sector cereals, and productivity changes for the whole agricultural sector are used as a proxy for the aggregated sector 'other crops'.

ENGAGE (ENvironmental Global Applied General Equilibrium) is a multi-region, multi-sector dynamic Computable General Equilibrium (CGE) model developed at UCL for the analysis of energy, environmental, resource and economic policies (Winning et al. 2017; Nechifor et al. 2019, Calzadilla et al. 2020). ENGAGE is based on the GTAP9-Power database (Peters, 2016) and represents the global economy in 2011. ENGAGE not only includes a detailed representation of different power technologies and energy related industries, it also represents other sectors of the economy (i.e. agriculture, industry and service sectors), allowing in this way the assessment of the economy-wide impacts of energy related policies and shocks. ENGAGE models 27 economic activities, 16 regions and 4 factors of production. Regarding the agriculture & food sector, ENGAGE models two individual crops (wheat and rice), two aggregated crops (cereals and 'other crops') and one aggregated food industry sector ('Agriculture and food').

The reference scenario with no climate change assumes that current climate conditions will persist into the future. In the reference scenario, economic growth in each region is calibrated to match the GDP growth behind the SSP2 pathway. In addition, regional demands are driven by the SSP2 population growth, and the economic structure in each region changes according to the SSP2 OECD projections. All climate change scenarios use the same assumptions as the reference scenario, but in addition, crop yield changes at different regional warming levels are introduced as shocks to the crops' land productivity.

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