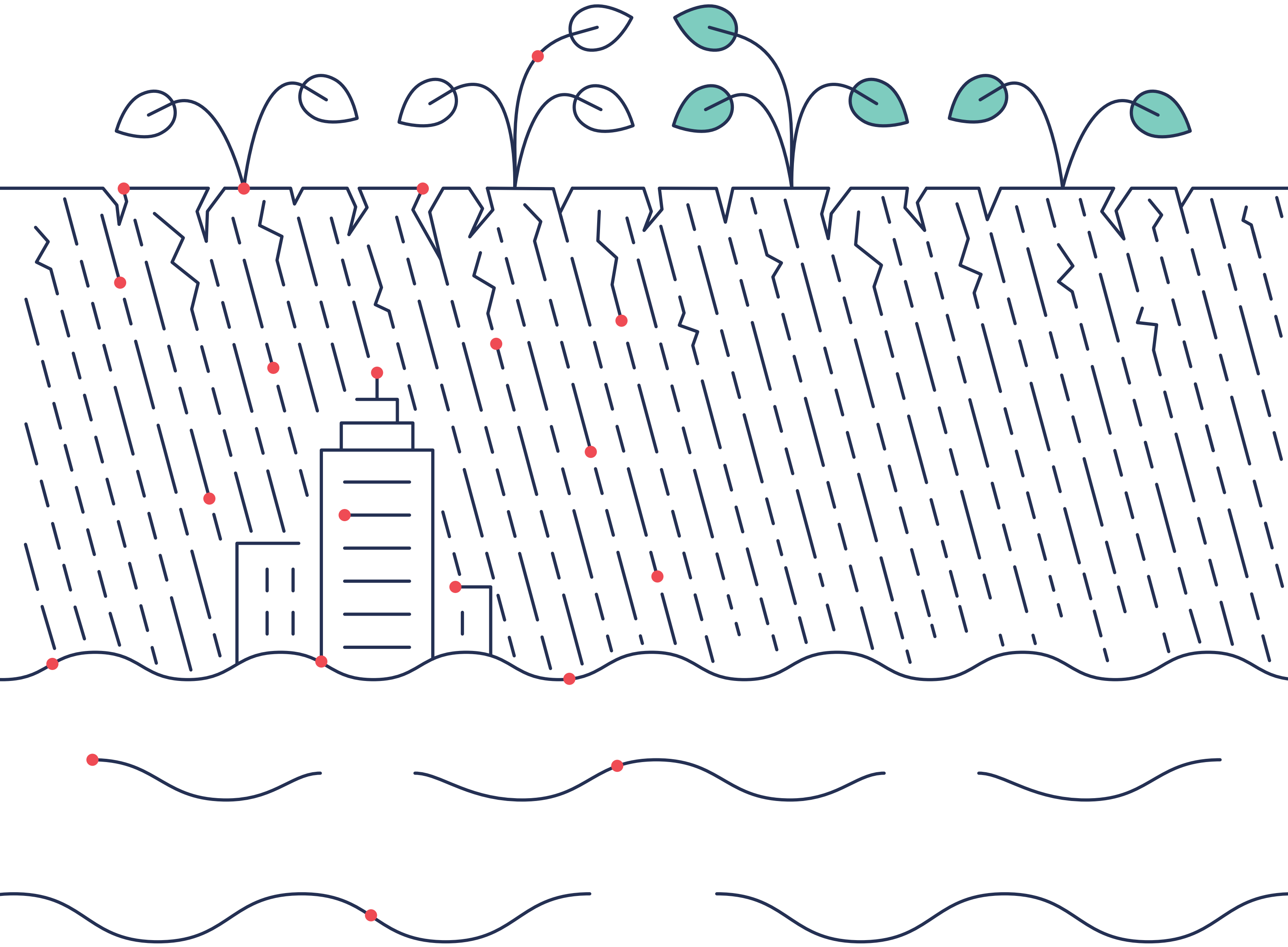
What will climate change cost the UK?

A study of climate risks, impacts and mitigation for the net-zero transition



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European Climate Foundation

Contents

Summary

Headline findings

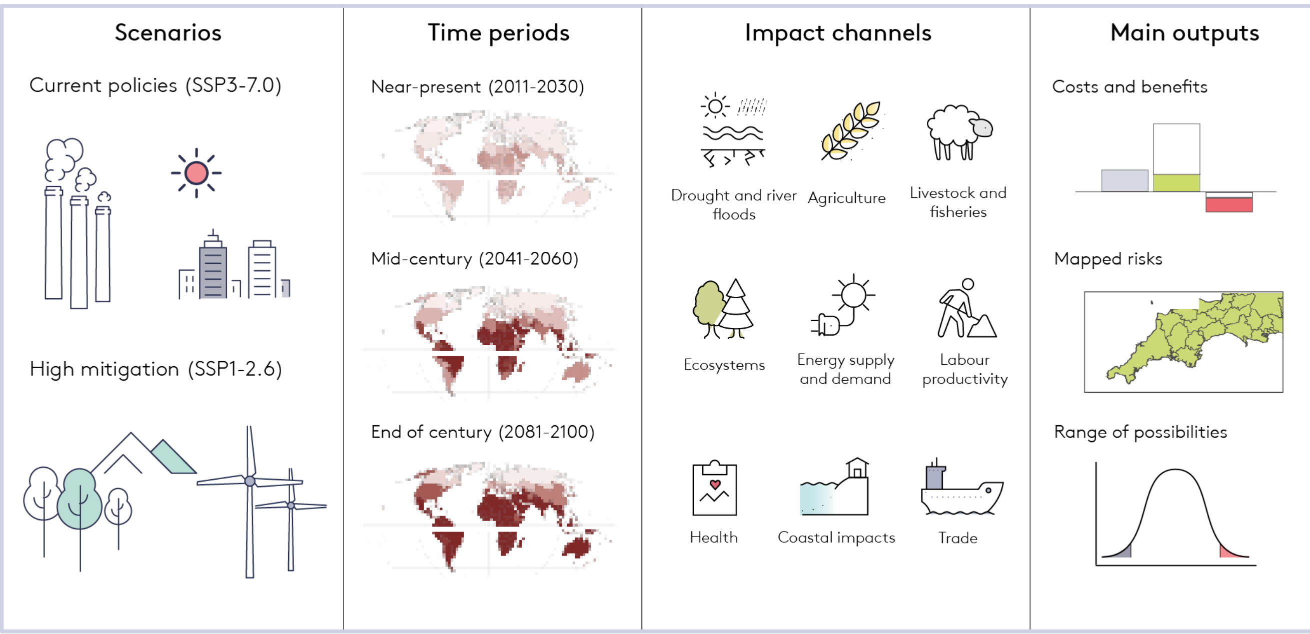
- **Under current policies**, the total cost of climate change damages to the UK are projected to increase from 1.1% of GDP at present to 3.3% by 2050 and at least 7.4% by 2100.
- **Strong global mitigation action** could reduce the impacts of climate change damages to the UK from 7.4% to 2.4% of GDP by 2100.
- The greatest risk to the UK under current polices is from **catastrophic disruption to the global economic system**.
- **Proactive investment in adaptation measures** such as coastal protection has the potential to reduce the risk of climate-related damages.
- **There are strong economic reasons for the drive to net-zero**: the benefits from mitigation exceed the costs at the global level in the second half of the century; there are significant co-benefits; and there is potential for boosting economic activity through investment.

Calculating the costs of climate impacts to the UK

Climate change poses numerous threats to society, including risks to the food system, biodiversity, infrastructure and human health. Through various impact channels, the term we use to describe particular pathways through which it can affect human welfare, climate change undermines and disrupts crucial sectors of the economy, incurring significant costs to business, investors and households.

This report estimates the total climate change risk for the United Kingdom based on an analysis of nine key impact channels, ranging from agriculture, livestock and fisheries to drought, flooding and coastal impacts. In each case, future impacts are translated into loss of socioeconomic welfare and reported as an equivalent loss of the UK's gross domestic product (GDP). We calculate these costs for two different scenarios: under current policies and with high mitigation climate policies.

Summary of the policy scenarios, time periods and impact channels studied in this report, and its main outputs



More than providing a stark warning of the future damage resulting from a lack of climate action, these estimates offer a helpful comparison between the costs of climate change impacts and the costs of mitigation efforts. We build on this to look specifically at the costs and benefits of net-zero policy and investments.

Overall climate costs

Under a current policies scenario, temperatures continue to rise, reaching 3.9°C of warming globally by 2100 (compared with the pre-industrial average), after accounting for tipping points. Compared with 1995–2005, the world is projected to warm by 3.2°C and the UK by 2.9°C by 2100. Consequently, total climate change costs are projected to increase from 1.1% of GDP at present to 3.3% by 2050 and 7.4% by 2100.

Strong mitigation policies can cap end-of-century temperatures to 2.1°C above the pre-industrial average, based on a high mitigation pathway that reaches net-zero globally around 2075. In this scenario, compared with 1995–2005, the world warms by 1.3°C and the UK warms by 0.8°C by 2100. This reduces the total projected end-of-century impacts to 2.4% of GDP, a benefit of 5 percentage points of GDP compared with current policies.

The largest risk under current policies is from catastrophic disruption to the global economic system (costing 4.1% of GDP by 2100). The greatest impact to UK GDP from the impact channels featured in this report comes from foreign trade (causing a 1.1% fall in GDP) as countries elsewhere in the world experience losses as a result of climate change.

Impact channels: overview

- **Droughts and flooding:** Drought risk increases rapidly after 2050 under current policies and there is a 1-in-20 chance that damages will be more than twice the expected level. Flood risk tends to occur in the same regions as drought risk and projected damages are similar in magnitude. The costs of drought and flooding under current policies total 0.21% of GDP, but only 0.05% of GDP under high mitigation.
- **Agriculture:** The weakening of Atlantic warming currents could devastate UK agriculture (which currently accounts for 0.6% of GDP), resulting in a 0.28% loss of GDP under current policies. This falls to 0.02% under high mitigation.
- **Livestock and fisheries:** Algal blooms attributable to climate change already cause £224 million of damage per year (0.01% of GDP) and this may double by 2100 under current policies. The expected costs across livestock and inland fisheries are projected to be 0.02% of GDP by 2100 under current policies, compared with 0.01% under high mitigation.
- **Ecosystems:** The welfare losses from global biodiversity decline outweigh the benefits of an expected increase in forest cover in the UK. The damages caused by biodiversity loss are projected to be 0.11% of GDP by 2100 under current policies, while forest growth will increase welfare by 0.06%. The combined loss would be 0.03% of UK GDP under high mitigation.
- **Energy supply and demand:** Both energy production costs and total demand are projected to decrease with warmer temperatures around 2050 before higher electricity production costs emerge in the late 21st century. The net effect remains less than 0.01% of the UK's GDP throughout the century.
- **Labour productivity:** Outdoor labour productivity declines in higher temperatures due to increased heat stress. While the effect globally increases rapidly over the century, the impact to the UK remains small (0.03% under current policies vs. 0.01% under high mitigation).

- **Health:** Benefits from less extreme winters in the North of the UK will be overshadowed by heat impacts across the country, increasing the death rate by 7.1 deaths per 100,000 people by 2100 under current policies (equivalent to a 0.4% reduction in GDP). Conversely, under high mitigation, the heat-related death rate will fall to 0.9 deaths per 100,000 people (equivalent to a 0.05% increase in GDP).
- **Coastal impacts:** Sea level rise could affect 5.4 million people in the UK, with expected damages of £68 billion by 2100 under current policies (0.56% of GDP), compared with £30 billion under high mitigation (0.25% of future GDP).
- **Trade effects:** For every 1% of GDP lost from its trading partners, the UK's GDP is projected to fall by about 0.16%. Based on this, the costs of climate change on other countries negatively impact UK GDP by 1.1% under current policies by 2100. Under high mitigation, this loss can be reduced to 0.06% of GDP.
- **Additional impact channels:** Climate risks can also emerge from many other possible channels, such as natural disasters, tourism, forestry, transport, conflict and displacement. We approximate these 'missing risks' as 25% of the estimated channels, or 0.7% of GDP by 2100 under current policies, compared with 0.2% under high mitigation.

The UK's net-zero pathway

We estimate that the mitigation costs involved in the UK's pathway to net-zero by 2050 are unlikely to exceed 2% of GDP over the transition period. Furthermore, mitigation policies bring co-benefits (to health outcomes, for example) and invigoration of the economy through investments. The effects of these co-benefits are likely to increase welfare equivalent to a 3.3% increase in GDP. Mitigation policy will provide a further boost of 2.8% to the UK's economy by stimulating investment in green industries and infrastructure.

Combined, the pathway to net-zero is expected to boost the UK's economy by over 4% of its GDP. Pursuing net-zero is therefore a 'no regret' policy, as it provides benefits to the UK economy even if global emissions do not fall enough to avoid the worst damages from climate change.

If other countries also reduce their carbon emissions in line with the UK, economic damages of over five percentage points of GDP would be avoided. We therefore estimate that the net economic benefits and avoided costs to the UK of rapid action to limit climate change (taken globally and in the UK) would be about 9.1% of GDP.

Summary of the costs of climate change as estimated for each impact channel

'Total costs' show the sum of the values below. **'Avoided costs'** show the difference between the current policies and high mitigation scenarios by the end of the century. **Ranges** (90% confidence intervals) are shown alongside.

	Current policies (% of UK GDP in 2081-2100)		High mitigation (% of UK GDP in 2081-2100)		Avoided costs (percentage points)	
Total costs	**7.44**	**0.07 – 16.17**	**2.36**	**-0.15 – 5.80**	**5.07**	**-0.68 – 3.20**
Drought and flooding	0.28	0.00 – 0.68	0.05	-0.01 – 0.16	0.23	-0.04 – 0.14
Agriculture	0.25	-0.02 – 0.59	0.02	-0.08 – 0.19	0.22	-0.16 – 0.27
Livestock and fisheries	0.02	0.02 – 0.03	0.01	0.00 – 0.02	0.01	0.00 – 0.01
Ecosystem	0.05	-0.04 – 0.19	0.03	-0.03 – 0.13	0.01	0.01 – 0.02
Energy supply and demand	0.00	-0.02 – 0.04	-0.01	-0.01 – 0.01	0.01	0.00 – 0.01
Labour productivity	0.03	0.00 – 0.06	0.01	0.00 – 0.02	0.02	-0.01 – 0.01
Health	0.40	-0.03 – 1.10	-0.05	-0.19 – 0.16	0.45	-0.08 – 0.31
Coastal impacts	0.56	0.04 – 1.51	0.25	0.03 – 0.86	0.31	-0.61 – 0.86
Trade	1.11	-0.28 – 3.17	0.64	-0.34 – 2.06	0.47	-0.50 – 0.71
Missing risks	0.67	0.19 – 1.33	0.24	-0.02 – 0.65	0.43	-0.15 – 0.36
Catastrophic damages	4.10	-2.80 – 11.87	1.17	-0.79 – 3.68	2.93	-0.41 – 2.41

1. Introduction

Many of the climate change impacts that the United Kingdom faces have the potential to create serious socioeconomic consequences. This report aims to provide improved estimates of the likely economic damages to the UK caused by climate change, highlighting where the greatest risks and adaptation needs are. These are presented as impacts to UK GDP under two different policy scenarios, enabling a comparison between the costs of climate change impacts and the cost of mitigation efforts until the end of the century.

1.1. Climate change risks in the UK

Climate change is already having noticeable and serious impacts around the world and will continue to do so for centuries. The recent Intergovernmental Panel on Climate Change (IPCC) Working Group II (WGII) Sixth Assessment report (AR6) on impacts, adaptation and vulnerabilities highlights several risks for the UK, including: 1.5 million people are at risk from two metres of sea level rise; suitable habitats for plants, insects and mammals are being degraded (particularly in the South); crops and fishery stocks are growing less productive; and flood risk is rising (IPCC, 2022).

While the worst of these impacts emerge under unmitigated climate change, some risks are considerable even at low levels of warming. Economic damages from river flooding are predicted to increase 1,200% in the UK even under 1.5°C warming, for example (Carbon Brief, 2018). London summers are predicted to become more deadly: the chance of avoiding heat-related summer deaths will drop from 10% to 2% under 2°C of warming, with heat-related mortality at levels exceeding the 2003 European heat wave occurring every other year (ibid.).

Box 1.1. Defining economic costs

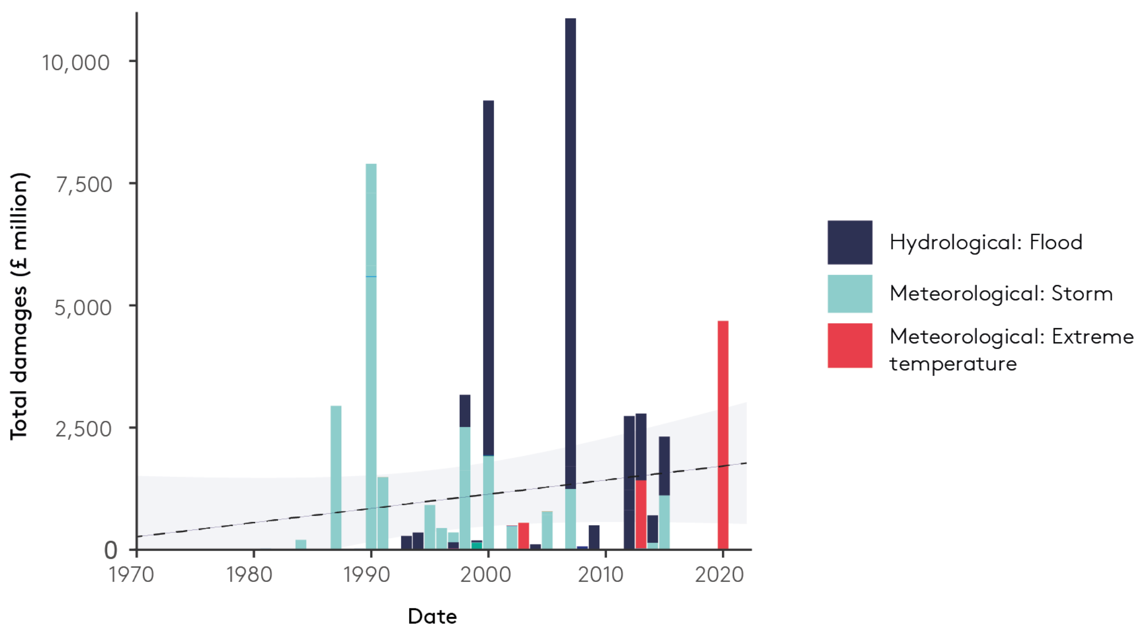
Economic losses represent the total loss to social and economic welfare as a result of climate change. How socioeconomic consequences are recognised depends on the application of a range of scientific and economic data. Climate change results in hazards, such as extreme storms, as projected using global climate models. These hazards have social consequences when people, and things that people care about, are exposed to them. The impact of these hazards then depends on the vulnerability of the system, which can be reduced through preparation and adaptation. When a system is impacted, its ability to support human welfare can be reduced, and the extent of socioeconomic resilience influences how much welfare is reduced (Hallegatte et al., 2016).

Economic assessments of climate change are intended to be comprehensive, capturing:

- Both market (e.g. agricultural production losses) and non-market (e.g. loss of biodiversity or risks of mortality and morbidity) damages (Rogers et al., 2019).
- Impacts of climate change evolving over centuries, including concomitant year-to-year disasters (DeFries et al., 2019).
- The inequality of impacts across groups and the uncertainty resulting from both climate and social dynamics (Rao et al., 2017).
- The potential of adaptation.

The rising risks of climate change to the UK are likely already reflected in the increase in damages resulting from natural disasters in the last five decades (see Figure 1.1). Storms, floods and extreme temperatures are some of the effects most clearly attributed to climate change, and these are all expected to increase. In the past decade the UK has experienced five heat waves, leading to over 3,300 deaths (CRED/UCLouvain, 2022; see Figure 1.1).

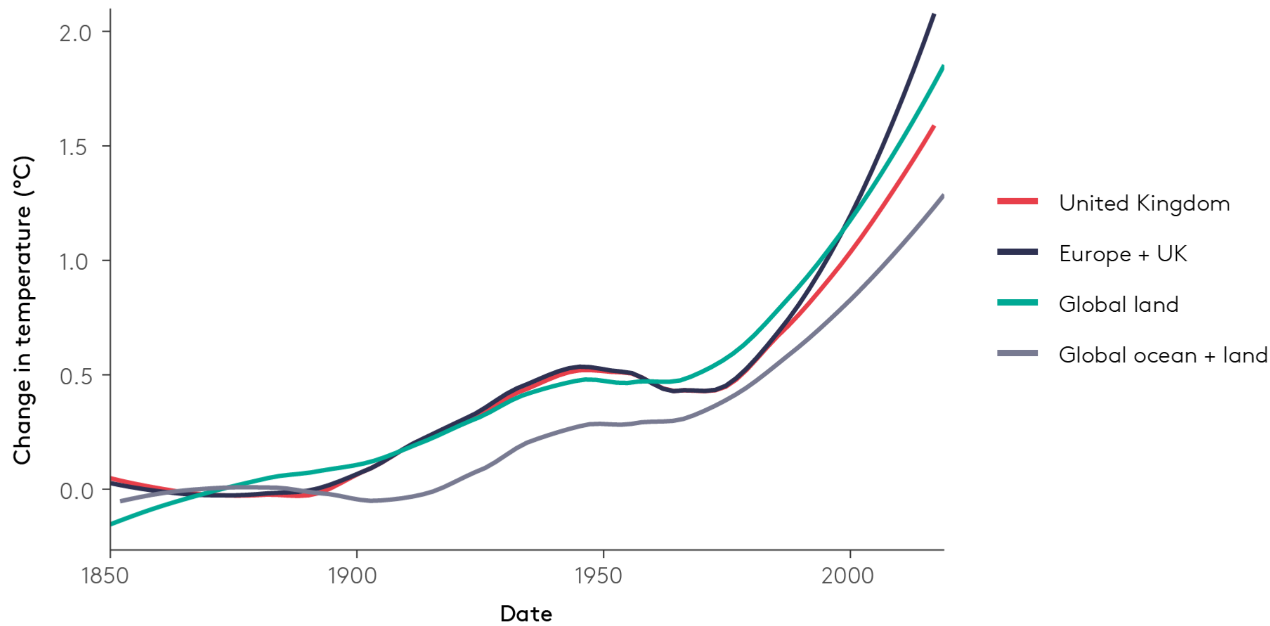
Figure 1.1. Costs of natural disasters in the UK, 1970–2020



Source: EM-DAT database (CRED/UCLouvain, 2022).
Notes: Total damages include reported damages (included insured damages), deaths valued at the value of a preventable fatality (£1.83 million), and people affected valued at one average month of lost income.

At the same time, the UK is comparatively insulated from a range of risks. Cooler baseline temperatures and the cushioning effect of the ocean are delaying many of the effects of climate change being felt by Southern Europe. The British Isles are expected to only experience, on average, two additional days per year over 30°C in a 3°C warmer world compared with 1971–2000. In recent decades, the UK has warmed more slowly than the Europe average, and more slowly than land globally (see Figure 1.2).

Figure 1.2. Temperature changes across the UK, Europe and the globe (relative to 1850–1900)



Source: Berkeley Earth BEST dataset (Rohde and Hausfather, 2020). [Smoothed with LOESS.]

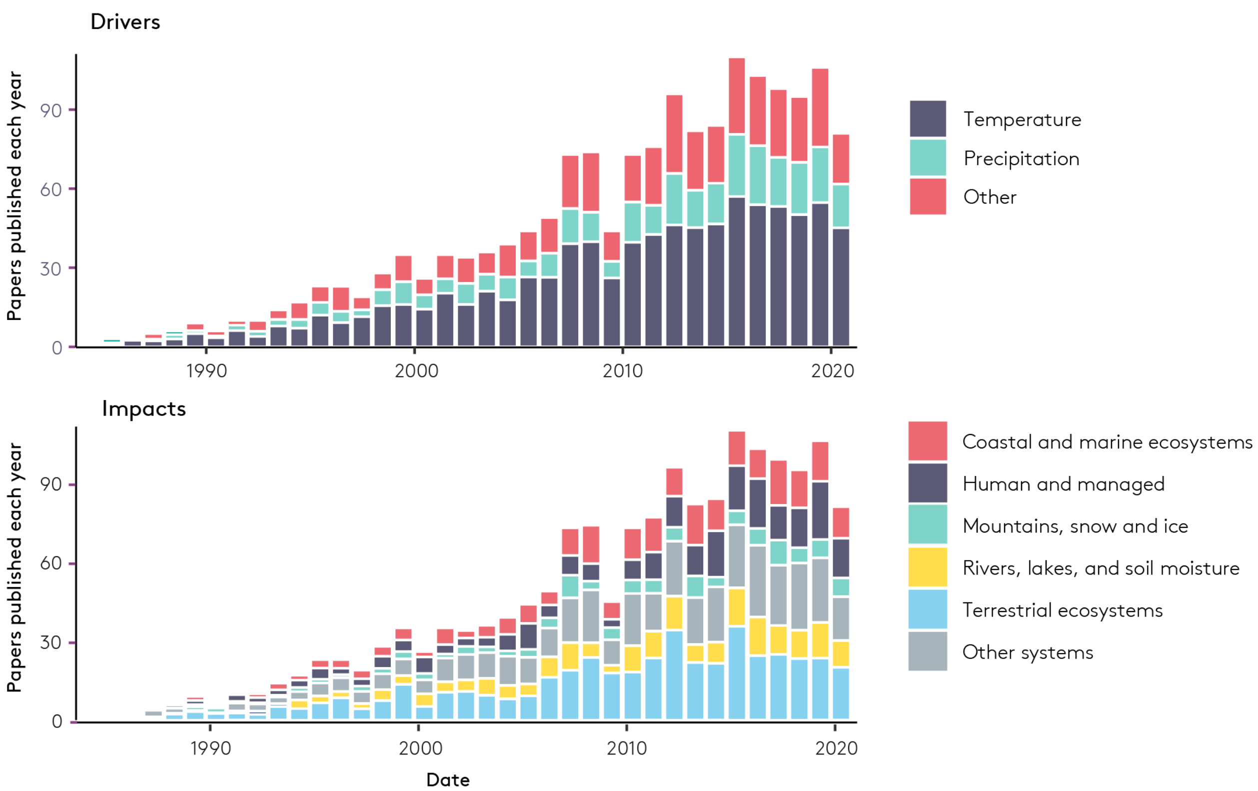
1.2. Research on climate change impacts on the UK and our investigation of 'impact channels'

To understand how these changes in the climate result in losses in human welfare and to the economy, we need to understand the UK's vulnerability to climate change as well as its capacity to adapt to it. Climate vulnerability depends on how much a group is dependent on its natural environment, how much time it spends outdoors, the quality of its infrastructure, and the protections it has developed against climate hazards. The UK is better equipped to avoid some climate impacts than other countries, with 73% of its economy in the service sector and only 0.58% in agriculture in 2020 (Statista, 2022a).

At the same time, much more work is needed to adapt to climate change in the UK. The Climate Change Committee's report of 2021 on adapting to climate change highlights the insufficient progress that has been made on preparation in most areas of risk (CCC, 2021). Proper adaptation planning requires a detailed understanding of what is at risk and why.

Research on climate impacts has increased rapidly over the past three decades, with around 1,400 published papers describing climate impacts in the UK since 2000 (see Figure 1.3). However, only 15% of these describe impacts on human and managed systems, despite their importance to society. Furthermore, available estimates of risks are rarely reported in economic terms. Recent evaluations performed under the IPCC Working Group II for the UK (Watkiss et al., 2021) and Germany (Kahlenborn et al., 2021) report semi-quantitative risk measures without attempting to combine them. Because of concerns about the low confidence of some results and the risk of double-counting, we rely on a much smaller collection of impact channels – specific pathways through which climate change can impact human welfare and the economy (see Table 1.1 below) – than these reports do.

Figure 1.3. Estimated number of academic papers on the risks of climate change in the UK, 1985–2020



Source: Callaghan et al., 2021.

The list of impact channels that this report investigates are summarised in Table 1.1 and the findings for each sector are provided in Section 3, with further details in the Annex.

Table 1.1. Channels of economic risk (impact channels) included in this study

Impact channel	Source	Methodology	Accounting for
Droughts and river floods			
Droughts	PESETA IV	Hydrological model – Empirical losses	Low flows
River floods	Sayers et al. (2020)	Hydrological model – Empirical losses	Fluvial, surface runoff
	PESETA IV	Hydrological model – Empirical losses	Flood inundation
Agriculture			
Agriculture	Ritchie et al. (2020)	Econometric	AMOC, rainfall, arable vs. grassland
	PESETA IV	Process-based	Wheat, grain maize, barley, sunflower, winter rapeseed, sugar beet
Livestock and fisheries			
Milk production	Jones et al. (2020)	Experiment-based	Temperature-humidity threshold
Lamb production	Jones et al. (2020)	Experiment-based	Parasite (*Hawmonchus contortus)*
Fisheries	Jones et al. (2020)	Experiment-based	Algal bloom temperature thresholds
Ecosystems			
Biodiversity loss (global)	IPCC AR4 WGII, Chapter 4	Meta-analysis	Habitat and species loss
Forest loss (UK)	Ritchie et al. (2019)	Process-based	Forestland change
Energy supply and demand			
Energy demand	Rode et al. (2021)	Econometric	Total electricity and other energy use
Electricity supply	PESETA IV	Process-based	Hydro, winds, solar, production costs
Labour productivity			
Labour productivity	PESETA III	Experiment-based	Temperature and humidity
Health			
Heat/cold-related mortality	Bressler et al. (2021)	Econometric synthesis	Temperature, income
	PESETA IV	Biophysical model	Heat- and cold-waves
Coastal impacts			
Coastal impacts	Diaz (2016)	Engineering model	Inundation, relocation, wetlands, protection
Trade effects			
Trade effects	Dell et al. (2012)	Econometric – CGE	Poor country GDP losses
	Burke et al. (2015)	Econometric – CGE	Non-linear GDP growth
	Kahn et al. (2021)	Econometric – CGE	Deviations from climatology
Additional impact channels			
Missing risks	Nordhaus (2013)	Expert elicitation	Fraction of known channels
Catastrophic risk	Howard and Sterner (2017)	Econometric synthesis	Global damage functions

Notes: These are often related to economic sectors, but not all of these channels have a corresponding market sector. AMOC = Atlantic Meridional Overturning Circulation. CGE = computational general equilibrium.

1.3. Our methods: estimates, mapping and scenarios

In addition to estimating economic costs from climate change, this report aims to improve upon past estimates in a few major ways. Firstly, it captures the full range of uncertainty, both from climate and impact uncertainty. Where possible, we use multiple models to account for deeper forms of uncertainty. Throughout the results, we report 5% and 95% quantiles of the uncertainty over economic risks (a 90% confidence interval). This reflects the 1-in-20 chance that damages will be greater than the 95% quantile value and recognises the important role that uncertainty plays in projecting future climate change: climate risks include the possibility of 'low-probability, high-negative' impact events, which have significant implications for decision-making around climate change (Weitzman, 2020).

Climate risks involve an abundance of impact channels that are difficult to quantify but are potentially decisive. We engage with these throughout the report, with discussions of what our current analysis misses and where more research is needed. We also incorporate these unknowns directly into our combined results. Following Nordhaus (2013), we include estimated losses from 'missing risks', estimated as a fraction of known risks. We also include a 'best estimate' of the risks of catastrophic climate change impacts, following Howard and Sterner (2017). The chance that such catastrophes will occur is small without considerable global warming, but the consequences would be large if they did.

The second major improvement to estimates of climate costs is that we develop our results at high spatial resolution to better inform adaptation planning across the UK. The regions used are described in Box 1.2.

Box 1.2. Spatial resolution

The UK uses a variety of statistical and administrative region designations. In this report, we use ADM3-level units, according to the GADM database version 3.4 (https://gadm.org/index.html). These consist of 406 regions, with 326 county districts, metropolitan boroughs and unitary authorities in England, 26 districts in Northern Ireland, 32 unitary districts in Scotland and 22 unitary authorities in Wales. These regions are shown in Figure 1.4.a.

The median ADM3 region area is 375 km^2. This compares well to the resolution of the downscaled climate data, which is 10 arc-minutes in latitude and longitude, or about 200 km^2. The grid cell comparison is shown in Figure 1.4.b.

Figure 1.4.a. Administrative divisions used for reporting impacts and economic damages (ADM3 regions)

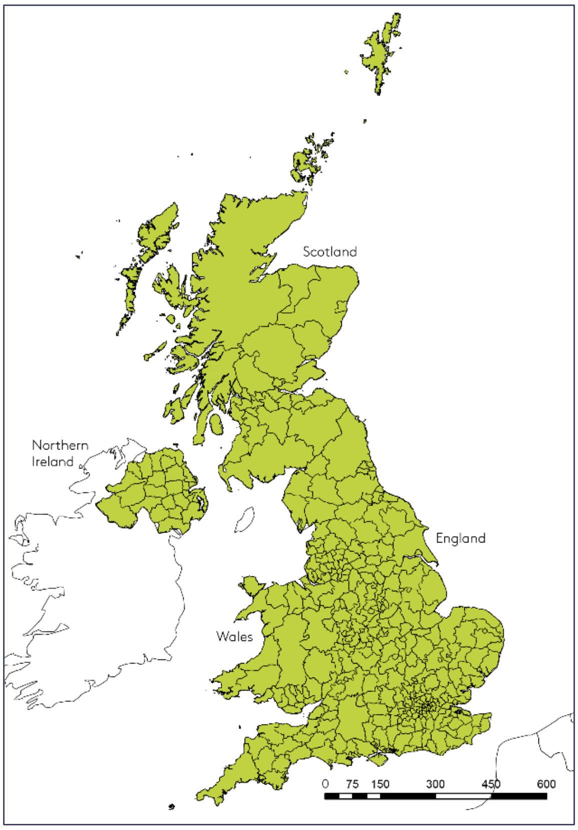


Figure 1.4.b. Downscaled climate data grid cells overlaid on the ADM3 regions

A third further improvement, and primary aim of this report, is to evaluate the various impact channels in a consistent set of scenarios, as described in Box 1.3 below. We compare a **current policies scenario** (SSP3-7.0), in which temperature rise reaches 3.9°C [3.0–4.9°C] [1] by 2081–42100, with a **high-mitigation scenario** (SSP1-2.6), in which temperatures stabilise at below 2.1 °C [1.4–2.8°C]. These levels of warming are slightly higher than those reported in the IPCC AR6 report (IPCC, 2022b) because of the additional effects of tipping points (see Annex A.2).

Relative to 1995–2005, the world will warm by 3.2°C [2.3-4.1°C] and the UK will warm by 2.9°C [1.2–4.5°C] under current policies. This is reduced by almost 2°C in each case under a high mitigation policy scenario, with the world warming by 1.3°C [0.7 – 2.1°C] and the UK by 0.8°C [-0.8–2.0°C].

[1] Ranges shown in square brackets to represent the 90% confidence interval.

Box 1.3. High-mitigation and low-mitigation scenarios

In this report, we apply the Shared Socioeconomic Pathways (SSPs) developed for the IPCC climate assessments. These scenarios describe future economic activity and the fossil fuel emissions that result from it. We compare two SSPs:

i) Current policies (SSP3-7.0)

The current policies (SSP3-7.0) scenario is characterised by a lack of increased climate policy ambition and global coordination. This results in faltering emissions reductions and a failure to invest strongly in green technologies and R&D. CO_2 emissions continue to increase through this century, with concentrations reaching 870 parts per million (ppm) in 2100 (current CO_2 concentrations are around 417 ppm).

The SSP3 storyline additionally describes regional rivalry at a global scale, resulting in persistent inequality, but our analysis does not depend on these details.

ii) High mitigation (SSP1-2.6)

The high mitigation (SSP1-2.6) scenario is characterised by sustainable action through strong investments in green technologies. Global emissions fall throughout the century and become net-negative after 2075 through carbon dioxide removal. CO_2 concentrations increase to a peak of 470 ppm before falling.

The SSP1 storyline also includes strong support for developing countries, but as before, these specifics do not affect our results.

We report the impacts and related costs to GDP for three periods:

- Present day (2011–2030)
- Mid-century (2041–2060)
- End of century (2081–2100)

The first period captures the impacts that are currently being experienced, to the extent that they can be attributed to climate change. We also include projected impacts decades into the future. Since the worst climate impacts in the latter part of the century depend on decisions made today, understanding their risks is crucial.

This work represents a range of cutting-edge studies on impact estimates translated into a consistent evaluation process. We include impacts from both process-based and statistical modelling approaches. We also use recent results on the economy-wide risks of climate change, which allow us to understand the spillover effects from climate damages occurring elsewhere around the world.

The evaluation performed here is not comprehensive. Within each impact channel, there are issues that are not captured. There are also a wide variety of channels of risk that remain understudied or could not otherwise be incorporated into this evaluation. In most cases, these omitted channels would be expected to further increase losses to the UK, which means that our result is likely to be an underestimate.

While economic costs are essential for conducting cost-benefit analysis, we consider such cost-benefit comparisons to be only one of many inputs into mitigation policy: in addition to the ethical and geopolitical reasons to stop climate change, mitigation investments have important benefits on their own (see Section 4). Furthermore, the analysis here is limited by only accounting for costs incurred by the population of the UK, while changes to mitigation policy will have impacts worldwide.

2. Overall climate costs: integrated damages

Climate change will have consequences for many aspects of society, which we refer to via our impact channels. As described in the Introduction, each impact channel is a particular pathway through which climate change can affect human welfare. For example, welfare is lost when changes in temperature and rainfall reduce crop productivity, as farmers get less income and consumers pay more for food. These channels are chosen to be as distinct as possible, to avoid double-counting the risks of climate change. In some economic risk assessments, channels are called 'sectors', since many of these channels result in losses to sectors of the economy, such as agriculture and industry. We use the phrase 'impact channels' as it is more general.

Some of these impacts, such as reductions in agricultural productivity, will have a direct monetary impact on the finances of people and companies. Others, such as impacts on biodiversity, cannot be expressed as a direct monetary equivalent. Nonetheless, they all affect human welfare in many ways.

Monetary and non-monetary impacts must be transformed into common units if we are to develop a comprehensive estimate of climate risk. This is done by understanding the trade-offs that people make when forced to choose between monetary and non-monetary goods. For example, we can ask if people would rather have cheaper cars or safer cars, and how much they are willing to spend for additional safety.

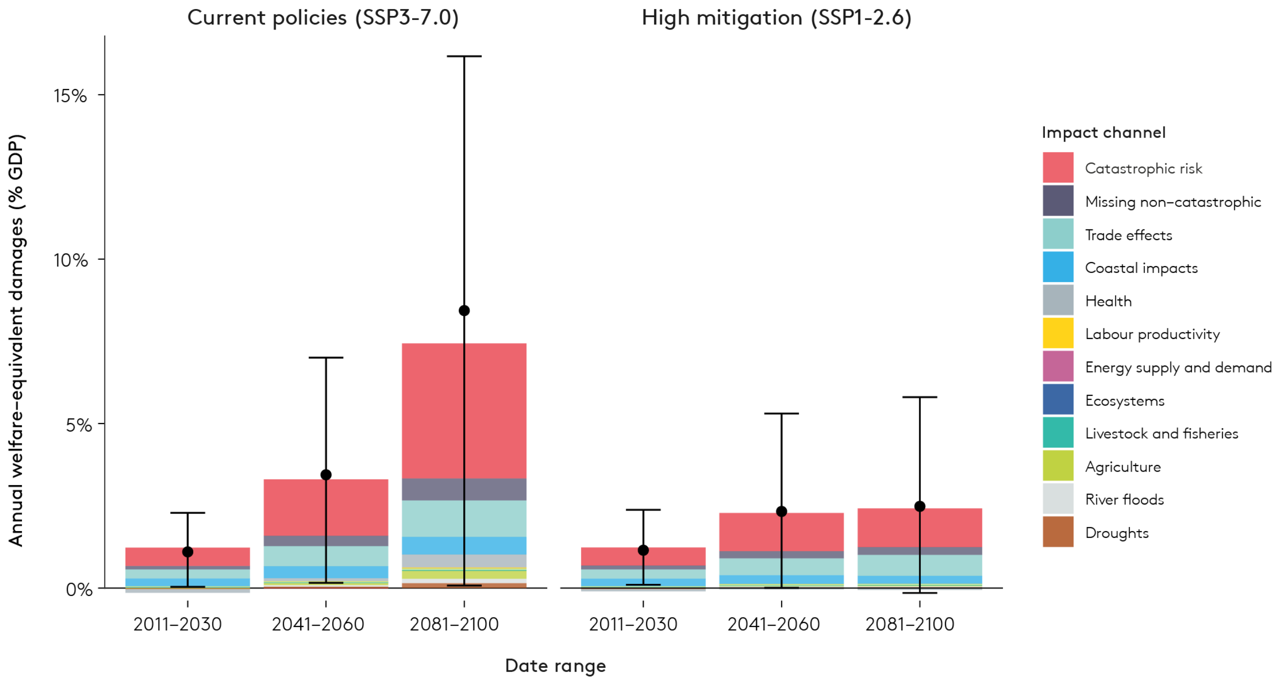
We report the losses for each of the impact channels as a percentage of current or future GDP, but they should also be understood as losses to welfare. Economists use the welfare benefits of increased incomes as a measuring stick for other kinds of welfare benefits, such as improvements in safety or protection of biodiversity. Reporting the losses calculated here in terms of the equivalent loss in GDP allows them to be directly compared with the costs of mitigation.

The losses are reported in Figure 2.1 for each scenario and each time period. **Under the current policies (SSP3-7.0) scenario, losses reach at least 7.4% of GDP by 2100. Under the high mitigation (SSP1-2.6) scenario, losses remain under 2.4% of GDP**.

We include two further categories of costs aside from those represented by our impact channels. First, following Nordhaus (2013), we include non-catastrophic missing risks equal to 25% of the total of the known channels. This increases current risks by about 0.1% but adds 0.7% to damages by 2100 under current policies. Second, we use the catastrophic damage calibration from Howard and Sterner (2017), which is calibrated to an analysis of 26 global damage functions, seven of which include catastrophic risks. Their analysis describes the incremental effect of catastrophic damages, on top of other global damages, and we use this increment. Although this describes global, not UK-specific, damages, we argue that a catastrophic event (defined as 25% or more of global GDP lost) would equally impact the UK. The specific mechanisms behind catastrophic risks are highly debated, with marine food webs, loss of pollination ecosystem services, extreme heatwaves, and migrant crises all plausible. Most likely, a catastrophic scenario would emerge from multiple interacting risks and cascading crises. If a climate catastrophe occurred, it is likely that multiple global supply chains would be disrupted, many people would lose their livelihoods, and national security would become a significant concern.

Figure 2.1 represents the risk of uncertainty in two ways. Error bars show the 90% confidence interval, representing the levels at which there is a 1-in-20 chance of lower damages and a 1-in-20 chance of higher damages. We also show a single point within this range, which represents the welfare loss of the risk itself, under risk aversion. This point is above the total impact level because facing the uncertainty adds to the loss of welfare. The total welfare damages (including risk aversion) for the current policies scenario at the end of the century is 8.5%, compared with 2.5% for the high-mitigation scenario. In the interest of presenting the uncertainty, rather than collapsing it into a single loss value, this risk averse certainty equivalent loss is not our main result.

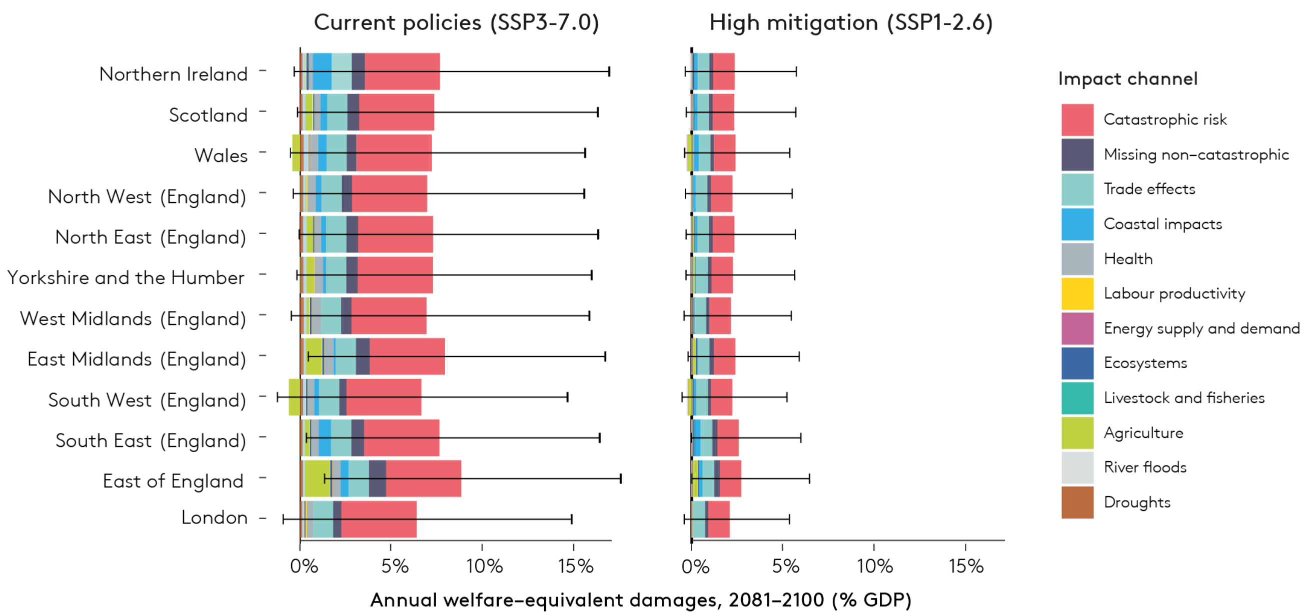
Figure 2.1. Total costs of climate change in the UK by sector



Notes: Error bars show 90% confidence intervals and points show certainty-equivalent damages, which price the uncertainty under risk aversion. Certainty-equivalent damages use an elasticity of marginal utility of 1.35 from Drupp et al. (2018).

Regional costs vary considerably, with total costs in some sub-regions amounting to more than 20% of local GDP. Figure 2.2 shows the spread of costs by region. The largest source of variation between regions is the effect of agricultural production losses, which depends on the importance of agriculture to the economy of the region in question, and the risks to it. The largest total projected losses occur along the East and South-East coasts of England, driven by a combination of agricultural losses and coastal impacts (see Figures 2.2 and 2.3).

Figure 2.2. Total climate change damages across the UK by sector, against estimated local GDP



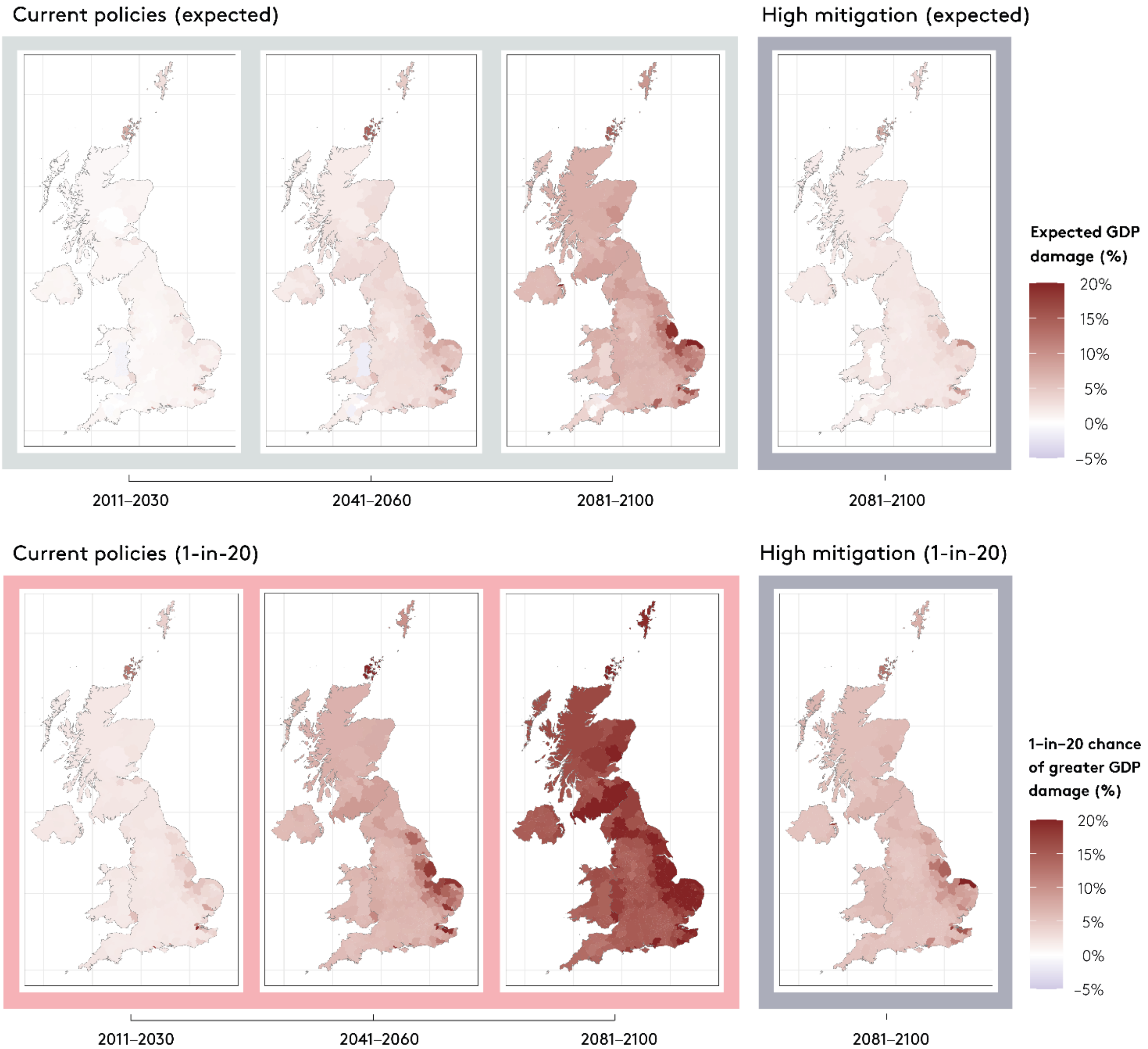
Note: Error bars show 90% confidence intervals.

Table 2.1. Total economic risks of climate change to the UK across all regions and impact channels, including the total of locally estimated damages, missing risks, and catastrophic damages

	Current policies (% GDP)			High mitigation (% GDP)			Avoided costs (% points)		
	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected change	1 in 20 more than
Total damages									
2011-2030	0.03	1.08	2.29	0.10	1.13	2.38	-0.77	-0.05	0.67
2041-2060	0.16	3.30	7.00	0.01	2.24	5.31	-0.68	1.05	3.20
2081-2100	0.07	7.44	16.17	-0.15	2.36	5.80	-0.34	5.07	11.53
Contributing results:									
Drought & inland flooding losses, including CGE effects, excluding double-counting									
2011-2030	-0.01	0.01	0.05	-0.01	0.01	0.04	-0.04	0.00	0.04
2041-2060	0.00	0.09	0.22	-0.01	0.04	0.15	-0.04	0.04	0.14
2081-2100	0.00	0.28	0.68	-0.01	0.05	0.16	-0.01	0.23	0.55
Best-estimate of losses to agriculture, including CGE effects									
2011 – 2030	-0.08	-0.03	0.05	-0.07	-0.02	0.05	-0.09	-0.00	0.09
2041 – 2060	-0.08	0.07	0.29	-0.09	0.02	0.19	-0.16	0.05	0.27
2081 – 2100	-0.02	0.25	0.59	-0.08	0.02	0.19	-0.06	0.22	0.56
Total annual damages across livestock and fisheries									
2011 – 2030	0.01	0.01	0.02	0.01	0.01	0.02	-0.00	0.00	0.00
2041 – 2060	0.01	0.02	0.02	0.01	0.01	0.02	-0.00	0.00	0.01
2081 – 2100	0.02	0.02	0.03	0.00	0.01	0.02	-0.00	0.01	0.02
Total welfare change from ecosystem impacts									
2011-2030	-0.01	0.02	0.09	-0.01	0.02	0.09	-0.01	-0.00	0.00
2041-2060	-0.03	0.03	0.14	-0.03	0.03	0.12	-0.01	0.00	0.02
2081-2100	-0.04	0.05	0.19	-0.03	0.03	0.13	-0.03	0.01	0.08
Total annual costs from energy supply and demand, including CGE effects									
2011-2030	-0.01	-0.01	-0.00	-0.01	-0.01	-0.00	-0.01	-0.00	0.01
2041-2060	-0.02	-0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.00	0.01
2081-2100	-0.02	0.00	0.04	-0.01	-0.01	0.01	-0.02	0.01	0.05
Annual labour productivity losses, including CGE effects									
2011 – 2030	0.00	0.00	0.01	0.00	0.00	0.00	-0.00	0.00	0.00
2041 – 2060	0.00	0.01	0.02	0.00	0.01	0.01	-0.00	0.00	0.01
2081 – 2100	0.00	0.03	0.06	-0.00	0.01	0.02	0.00	0.02	0.04
Best-estimate heat/cold mortality, change in death rate									
2011 – 2030	-0.18	-0.11	-0.04	-0.14	-0.07	0.00	-0.14	-0.04	0.06
2041 – 2060	-0.06	0.08	0.29	-0.15	-0.03	0.16	-0.08	0.12	0.31
2081 – 2100	-0.03	0.40	1.10	-0.19	-0.05	0.16	0.04	0.45	1.08
Total damages from coastal impacts, including CGE effects									
2011-2030	0.06	0.24	0.53	0.06	0.24	0.55	-0.43	0.00	0.42
2041-2060	0.06	0.37	1.01	0.04	0.28	0.78	-0.61	0.09	0.86
2081-2100	0.04	0.56	1.51	0.03	0.25	0.86	-0.65	0.31	1.37
Best-estimate of trade losses									
2011 - 2030	0.06	0.27	0.54	0.05	0.28	0.58	-0.26	-0.00	0.23
2041 - 2060	0.02	0.61	1.49	-0.05	0.51	1.34	-0.50	0.10	0.71
2081 - 2100	-0.28	1.11	3.17	-0.34	0.64	2.06	-0.77	0.47	1.85
Missing risks cost estimate									
2011-2030	0.01	0.11	0.22	0.02	0.12	0.23	-0.14	-0.01	0.12
2041-2060	0.09	0.32	0.61	0.02	0.22	0.49	-0.15	0.10	0.36
2081-2100	0.19	0.67	1.33	-0.02	0.24	0.65	-0.03	0.43	0.96
Catastrophic damage risk									
2011 – 2030	-0.37	0.55	1.60	-0.37	0.55	1.60	-0.25	0.01	0.28
2041 – 2060	-1.14	1.71	5.02	-0.78	1.16	3.58	-0.41	0.55	2.14
2081 – 2100	-2.80	4.10	11.87	-0.79	1.17	3.68	-1.97	2.93	8.56

Note: See Box 2.1 for further details on how to interpret this table.

Figure 2.3. The expected costs of climate change by region as a percentage of local GDP under current policies and high mitigation: expected (top) and the 1-in-20 chance that damages will be greater than the expected range (bottom)



Notes: These values correspond to the total impacts in Figure 2.1 and Table 2.1.
See Box 3.1 for further details on how to interpret these maps.

3. Impact channels

This section provides more detailed information on the climate change costs for each impact channel. For each one, we provide an overview, outline our approach, present the main projection results, and recognise the risks not captured in the estimates. The order of the channels as presented roughly progresses from costs most closely related to physical impacts to costs informed by more complex processes.

The projection results are summarised in a table reporting the expected change under each emissions scenario and the tail risks, reported as the value for which there is a 1-in-20 chance that the true result will be below, and the value for which there is a 1-in-20 chance of it being above, the expected calculation (these give the 90% confidence interval). We then report the benefits of mitigation, which represents the difference in costs between the high- and low-mitigation scenarios, and its range of uncertainty (see Box 3.1).

Box 3.1. How to interpret the tables and maps

Tables show UK-wide welfare losses across time periods and scenarios.

	Current policies (% GDP)			High mitigation (% GDP)			Avoided costs (% points)		
	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected change	1 in 20 more than
Total damages									
2011-2030	0.03	1.08	2.29	0.10	1.13	2.38	-0.77	-0.05	0.67
2041-2060	0.16	3.30	7.00	0.01	2.24	5.31	-0.68	1.05	3.20
2081-2100	0.07	7.44	16.17	-0.15	2.36	5.80	-0.34	5.07	11.53

The right-hand columns show the percentage point difference between current policies and high mitigation.

Most likely estimates are shown in **darker columns**

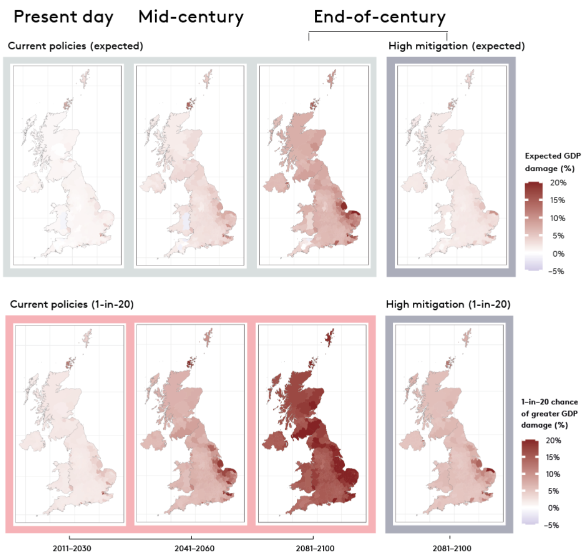
There is a **1-in-20 chance** that **losses will be greater** than these values

Note: Totals and differences reported in the tables may not exactly match, due to rounding.

Maps show local welfare losses across time periods and scenarios.

Most likely estimates

1-in-20 chance that losses will be greater than the expected range



The first three columns show results for current policies. The right-hand column gives a high-mitigation scenario comparison.

Following each discussion is a map of the impacts across the UK. An overview of the projection method used consistently across the impact channels is described in Annex A.

The main results reported in these sections and in the corresponding maps are generally in units most directly related to the underlying study. These are converted to percentages of GDP to produce the results shown in the previous section on integrated damages.

3.1. Droughts and river floods

Overview

Global warming has resulted in the increased frequency and intensity of droughts and river (fluvial) flooding, causing health issues, economic losses and damage to infrastructure. The recent drought in 2018–2019 caused water use restrictions, fish fatalities and wildfires. During that drought, 537 incidents were logged by the Environment Agency and Scottish Environment Protection Agency, with impacts on ecosystems, water quality and supply, transport, agriculture and health.

Each year, flooding results in £1.3 billion in losses to the UK (Environment Agency, 2018a). Flooding can cause significant damage to physical transport and utilities infrastructure, including roads, bridges and railways, and water, electricity and telecommunications networks. For example, during the 2015–2016 winter floods in the North of England which followed Storms Desmond, Eva and Frank, the Highways Agency recorded 850 road flooding incidents on the strategic road network while the inundation of a power substation in Lancaster caused intermittent power cuts, affecting more than 100,000 people and lasting for up to three days (Environment Agency, 2018a). It is projected that river flooding will account for about £40 billion per year in losses in a 3°C warmer climate in 2100 (PESETA IV). These risks will be further exacerbated by a rise in population. According to Sayers et al. (2020), the population in flood-prone areas is projected to grow by up to 2.6 million by mid-century under a 2°C warmer scenario and by 3.3 million under a 4°C warmer scenario.

Our approach

We draw on results from the PESETA IV[2] analyses on droughts and river floods which use the widely used LISFLOOD hydrological model (Van Der Knijff et al., 2010). We also project estimates from the *Climate Change Risk Assessment 2017 Projections of future flood risk in the UK* report (Sayers et al., 2020), which has total flooding damage estimates for coastal, fluvial and surface flooding. We focus on estimates of fluvial and surface flooding by deducting coastal flooding damages from the total damages.

Projections

Drought-related damages reach 0.25% of GDP and flooding damages reach 0.13% of GDP by the 2100 under current policies (SSP3-7.0). The Midlands are a significant centre of these risks, although losses are expected to occur across the UK.

A portion of drought risks is included separately in the Agriculture channel (Section 3.2), but the total additional risk from droughts and inland flooding results in 0.28% of GDP by 2100.

[2] The 'Projection of economic impacts of climate change in sectors of the European Union based on bottom-up analysis' project.

Table 3.1. UK-wide costs to welfare from droughts and river flooding

	Current policies (% GDP)			High mitigation (% GDP)			Avoided costs (% points)		
	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected change	1 in 20 more than
Drought damages from PESETA IV, including CGE effects									
2011-2030	-0.02	0.01	0.05	-0.02	0.01	0.04	-0.04	0.00	0.04
2041-2060	-0.00	0.08	0.20	-0.01	0.04	0.13	-0.04	0.04	0.14
2081-2100	0.01	0.25	0.62	-0.01	0.04	0.14	-0.01	0.21	0.52
Best-estimate flooding effects, including CGE effects									
2011 – 2030	-0.01	0.01	0.03	-0.01	0.01	0.03	-0.03	0.00	0.03
2041 – 2060	-0.01	0.04	0.12	-0.02	0.02	0.09	-0.04	0.02	0.09
2081 – 2100	-0.02	0.13	0.36	-0.01	0.02	0.08	-0.03	0.10	0.31
Contributing model results:									
River floods from PESETA IV, including CGE effects									
2011-2030	-0.03	0.03	0.09	-0.03	0.03	0.09	-0.08	0.00	0.08
2041-2060	-0.00	0.12	0.29	-0.02	0.07	0.22	-0.10	0.05	0.21
2081-2100	0.02	0.33	0.84	-0.02	0.07	0.22	-0.03	0.26	0.71
Fluvial and surface water floods from Sayers et al. (2015), including CGE effects									
2011 – 2030	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	0.00
2041 – 2060	-0.00	0.00	0.01	-0.00	-0.00	0.00	-0.00	0.00	0.01
2081 – 2100	-0.00	0.02	0.05	-0.00	0.00	0.01	-0.01	0.02	0.05

Notes: The rows report total drought costs and best-estimate river flooding costs (informed by the PESETA IV model results and river flooding costs from Sayers et al. [2015].

Figure 3.1.a. Expected costs of drought and river flooding by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)

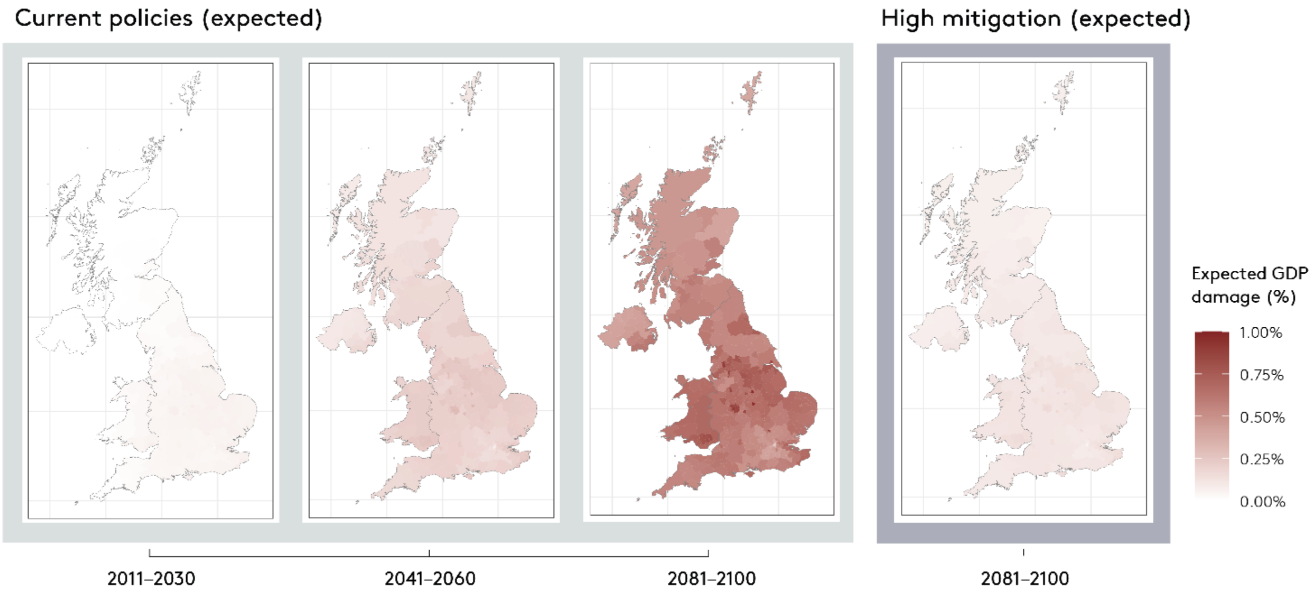
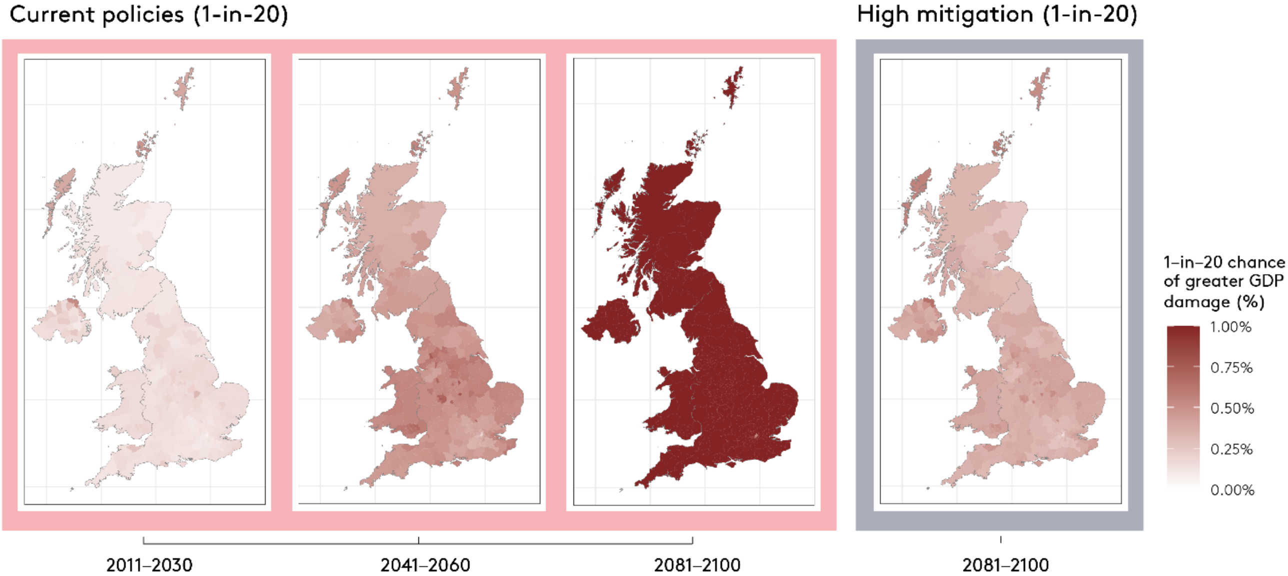


Figure 3.1.b. High-risk costs of drought and river flooding by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)



What we miss

The extent of economic damages accounted for in this report is limited to direct damages, including those to buildings and economic assets. However, losses go beyond the likes of property. Droughts and flooding result in agricultural losses (only partially captured by the Agriculture channel, Section 3.2), health impacts and diseases (only partially captured by the Health channel, Section 3.7). The full damages from drought and flooding also include business disruption (e.g. industrial or mining stoppages due to curtailed access to water and supply chain failures when transport is impacted by floods). As a result, the values presented here are an underestimate of the total drought- and flooding-related climate damages to the UK.

3.2. Agriculture

Overview

Crop production contributed £9 billion to the UK economy in 2020 (Department for Environment, Food and Rural Affairs [Defra], 2020), representing 34% of agriculture's total contribution to the economy. Together, cereals including wheat and barley and fresh vegetables, plants and flowers made up over 60% of the total crop output (ibid.) (at market prices). Farming's place in rural life remains close to the heart of British culture and identity, yet the risks to agriculture are some of the starkest in this report. As the East and South-West regions become drier, arable land is at risk of disappearing (Ritchie et al., 2019). These risks increase with the potential weakening of the Atlantic Meridional Overturning Circulation (AMOC), an ocean conveyor-belt of waters that warm Europe (Ritchie et al., 2020). The weakening of the AMOC would likely cause large reductions in rainfall in the UK, which could make most land unsuitable for arable farming (ibid.).

Our approach

We rely on the estimates of arable land from Ritchie et al. (2019), which use the ECOnometric aGricultural land use model (ECO-AG). We assume that agricultural production will reduce or increase from its baseline level proportionally to the increase or decrease in arable land. We also draw on the results from PESETA IV and combine these into a single estimate through meta-analysis.

Projections

The economic impacts of climate change on agriculture are very different in the two sources used (see 'Our approach'), with PESETA IV describing benefits from climate change up until mid-century while Ritchie et al. shows damages of £16.7 billion per year. Our combined effect treats this difference as a kind of model uncertainty. These losses are driven by reductions in rainfall, following a weakening of the AMOC system. Considerable expansion of irrigation would reverse some of this effect, but we do not include this adaptation as we cannot identify how it would be implemented.

The best estimate of losses to the agricultural sector is about 0.25% of GDP by the end of the century (roughly £5.1 billion per year in the current economy). This is nearly half of the direct contribution of agriculture to the UK economy (which accounts for around 0.6% of GDP), partly due to the considerable aggravating effects of agricultural supply chain disruption.

Table 3.2. Impacts of climate change on the agricultural sector

	Current policies (% GDP)			High mitigation (% GDP)			Avoided costs (% points)		
	1-in-20 less than	Expected	1-in-20 more than	1-in-20 less than	Expected	1-in-20 more than	1-in-20 less than	Expected change	1-in-20 more than
Best-estimate of losses to agriculture, including CGE effects									
2011 – 2030	-0.08	-0.03	0.05	-0.07	-0.02	0.05	-0.09	-0.00	0.09
2041 – 2060	-0.08	0.07	0.29	-0.09	0.02	0.19	-0.16	0.05	0.27
2081 – 2100	-0.02	0.25	0.59	-0.08	0.02	0.19	-0.06	0.22	0.56
Contributing model results:									
Ritchie et al. (2019) loss estimate without AMOC									
2011 – 2030	-0.19	-0.13	-0.08	-0.18	-0.12	-0.07	-0.05	-0.01	0.04
2041 – 2060	-0.28	-0.23	-0.16	-0.27	-0.19	-0.04	-0.14	-0.05	0.02
2081 – 2100	-0.40	-0.29	-0.17	-0.27	-0.15	0.17	-0.35	-0.14	-0.04
Ritchie et al. (2019) loss estimate with potential AMOC									
2011 – 2030	-0.15	-0.04	0.15	-0.14	-0.03	0.14	-0.22	-0.01	0.20
2041 – 2060	-0.15	0.16	0.64	-0.18	0.06	0.41	-0.34	0.10	0.60
2081 – 2100	-0.08	0.49	1.19	-0.18	0.08	0.45	-0.20	0.42	1.16
PESETA IV loss estimate									
2011 – 2030	-0.12	-0.05	0.02	-0.12	-0.05	0.01	-0.10	0.00	0.10
2041 – 2060	-0.12	-0.05	0.03	-0.12	-0.05	0.03	-0.11	0.00	0.11
2081 – 2100	-0.08	0.01	0.15	-0.12	-0.04	0.04	-0.06	0.06	0.20

Notes: All results include general equilibrium effects that account for how agricultural losses affect other sectors of the economy.

Figure 3.2.a. Expected costs of agricultural productivity by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)

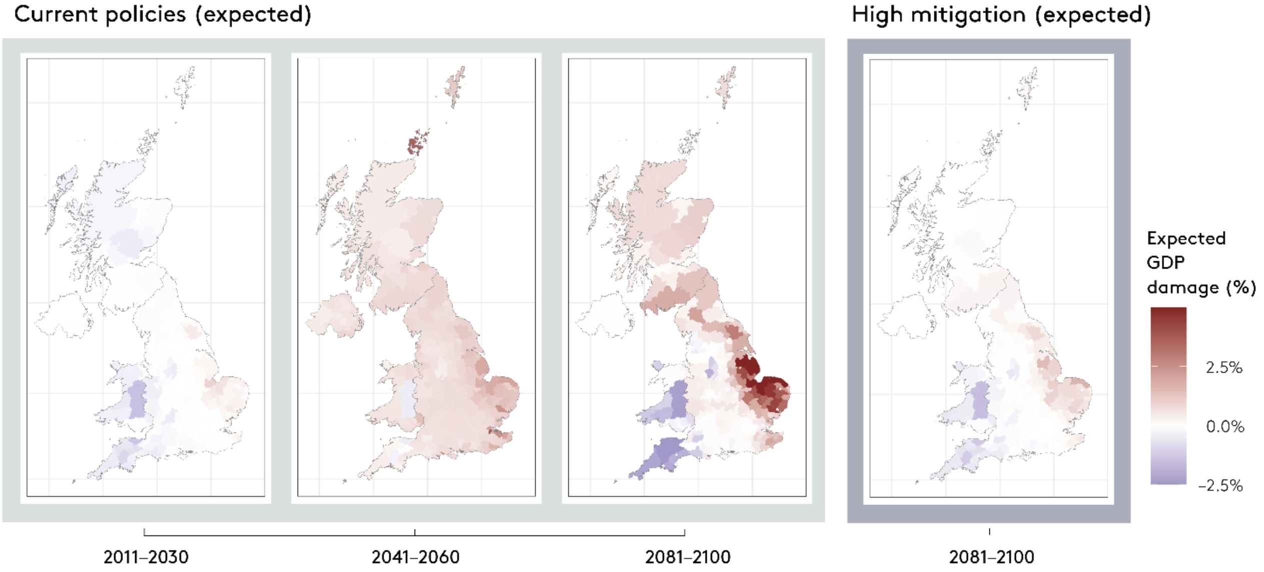
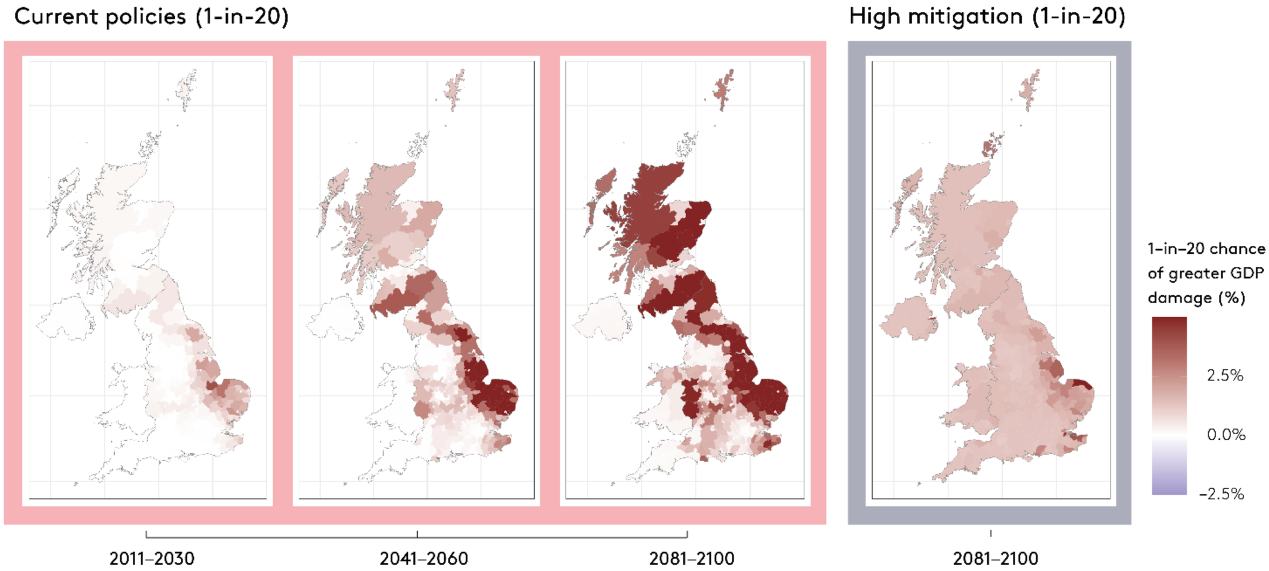


Figure 3.2.b. High-risk costs of agricultural productivity by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)



Note: Combined across Ritchie et al. (2019) and PESETA IV.

What we miss

Our models of agriculture are incomplete. The PESETA IV results only include five major grains, accounting for about 70% of cropped land in the UK. All other crops are assumed to be unaffected by climate change, despite considerable evidence that many crops are susceptible to heat stress (Lobell et al., 2008). The changes to arable land from Ritchie et al. do not account for the effects of CO_2 fertilisation, which is expected to increase the yields of many crops. Between the limited range of crops, likely producing an underestimate, and the exclusion of CO_2 fertilisation from some models, likely producing an overestimate, the net effect is unclear.

3.3. Livestock and fisheries

Overview

Livestock production contributed £15 billion to the UK economy in 2020 (Defra, 2020), representing 56% of the total agriculture sector. Rising temperatures could have significant negative impacts on livestock production. When exposed to high temperatures, farm animals are vulnerable to heat stress and their growth, milk production and reproductive efficiency can be impaired (Nardone et al., 2010). Climate change may also enable shifts in the distribution of diseases, especially vector-borne and parasitic diseases, which can affect animal health (ibid.).

While the fishing industry represents only 0.03% of the UK's total GDP, estimated at £430 million in 2020 (Uberoi et al., 2021), recreational fishing accounts for about £1.5 billion with 980,000 registered anglers in England (Environment Agency, 2018b). Warmer temperatures can contribute to a higher incidence of algal blooms in UK lakes and rivers (Jones et al., 2020). Algal blooms can have a range of negative impacts, including health impacts for humans and animals – in particular, fish fatality in freshwater fisheries – and reduced potential for recreational fishing at affected sites (Cheung et al., 2013).

Our approach

We rely on results from Jones et al. (2020), which model changes in algal bloom intensities, heat stress on milk-producing cows and the effect of *Haemonchus contortus* parasite on lambs. In each case, a particular environmental temperature threshold is identified from the literature, which allows future heat waves to be translated into losses.

Projections

The evolution of costs across the three sectors included in Table 3.3 depends on the underlying environmental thresholds. With the lowest threshold, lamb production is most vulnerable: losses are incurred when the daily mean temperature is above 9°C – a level that is already exceeded in many regions. Milk production is reduced under a combination of higher temperature and humidity, but roughly corresponds to a threshold of 23°C, which means that the largest impacts are not observed until the end of the century. The greatest impacts come from algal blooms, with an intermediate threshold of 17°C, driven by the considerable baseline costs of £75–114.3 million per year (Pretty et al., 2003). Despite these large numbers, the total cost of damages across the three sectors remains a small fraction of the UK's GDP.

Table 3.3. Costs due to damages to livestock, fisheries and algal blooms

	Current policies (% GDP)			High mitigation (% GDP)			Avoided costs (% points)		
	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected change	1 in 20 more than
Total annual damages across livestock and fisheries									
2011 – 2030	0.01	0.01	0.02	0.01	0.01	0.02	-0.00	0.00	0.00
2041 – 2060	0.01	0.02	0.02	0.01	0.01	0.02	-0.00	0.00	0.01
2081 – 2100	0.02	0.02	0.03	0.00	0.01	0.02	-0.00	0.01	0.02
Contributing model results:									
Annual economic losses in lamb production									
2011 – 2030	0.0012	0.0016	0.0020	0.0011	0.0016	0.0020	-0.0005	0.0000	0.0005
2041 – 2060	0.0016	0.0020	0.0024	0.0011	0.0018	0.0024	-0.0004	0.0002	0.0009
2081 – 2100	0.0007	0.0019	0.0025	0.0001	0.0016	0.0024	-0.0014	0.0002	0.0018
Annual economic losses in milk production									
2011 – 2030	-0.0000	0.0001	0.0002	-0.0000	0.0001	0.0002	-0.0001	0.0000	0.0001
2041 – 2060	0.0001	0.0004	0.0008	-0.0000	0.0002	0.0006	-0.0000	0.0002	0.0004
2081 – 2100	0.0001	0.0010	0.0022	-0.0000	0.0002	0.0006	0.0001	0.0008	0.0017
Annual economic losses due to algal blooms									
2011 – 2030	0.0072	0.0108	0.0147	0.0071	0.0107	0.0144	-0.0046	0.0001	0.0048
2041 – 2060	0.0103	0.0152	0.0196	0.0066	0.0126	0.0179	-0.0040	0.0026	0.0095
2081 – 2100	0.0125	0.0184	0.0237	0.0012	0.0112	0.0180	-0.0016	0.0072	0.0182

Figure 3.3.a. Expected costs of livestock and fisheries by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)

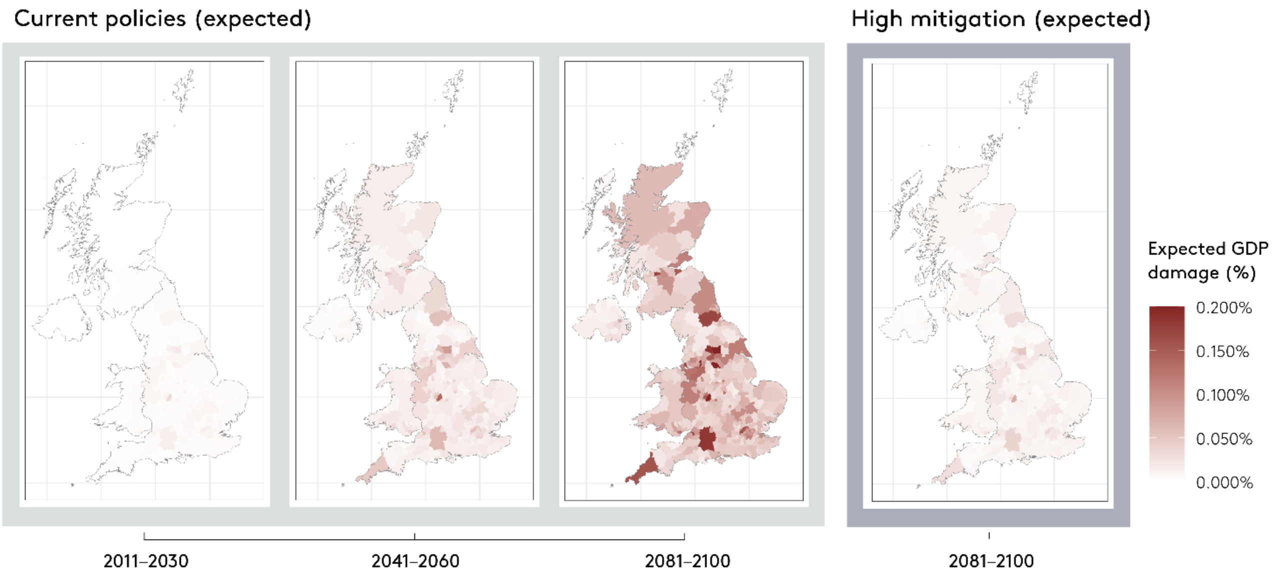
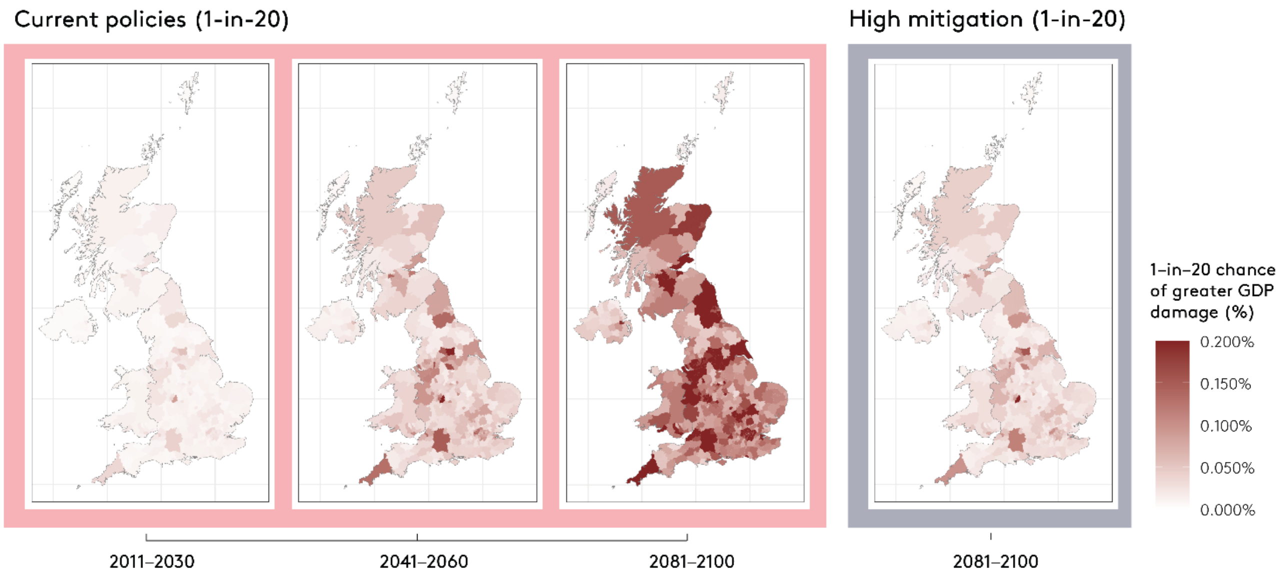


Figure 3.3.b. High-risk costs of livestock and fisheries by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)



What we miss

These calculations only consider lamb meat and milk production, which represent 40% of the UK's livestock production value in 2020. Beef (23%) and poultry (20%) contribute the next largest shares. There are also other drivers of productivity loss for livestock that are not captured (e.g. temperature-dependent diseases for milk and disease-independent productivity losses for lamb growth) (Nardone et al., 2010). It is likely that the effects of a warming climate on the full livestock sector as presented here are a considerable underestimate.

The results for algal blooms do not account for an important adaptation pathway: algal blooms are driven by elevated nutrients, typically from farm runoff. The results are based on a static assessment of lakes at high risk of harmful algal blooms, and these are likely to change in the future. Depending on land use policy, algal blooms could increase or decrease from the historical relationships.

3.4. Ecosystems

Overview

The *Dasgupta Review* on the economics of biodiversity (Dasgupta, 2021) highlights that climate change is one of many risk factors for biodiversity. Climate change is already contributing to changes in phenology (seasonal and life-cycle events in biological systems) and the distribution of species and population sizes, which can lead to changes in the amount and distribution of genetic diversity. In the UK, the genetic diversity of many species is being reduced, thus increasing the risk of extinction for these species (LWEC, 2015). Biodiversity protection can be considered an end in itself, or as contributing to a range of 'ecosystem services'. Ecosystem services are crucial to humans and the economy, bringing both direct quantifiable benefits, such as pollination and air quality, and personal and cultural benefits, such as aesthetics, learning and inspiration (Díaz et al., 2019).

Our approach

Biodiversity losses around the globe result in welfare losses within the UK. Estimates of biodiversity loss globally are based on a collection of habitat and species impacts from the IPCC WGII Fourth Assessment report (2007), valued as the UK's willingness to pay for biodiversity protection (Nobel et al., 2020).

We also include the impacts of climate change on UK forests and the ecosystem services they provide. This relies on modelling performed within the Ritchie et al. (2019) study, using the Joint UK Land Environment Simulator (JULES). The JULES model describes changes in multiple land use types, including forest cover of broadleaf and needleleaf trees. To translate the changes into economic terms, we use Willis et al. (2003), who account for both local benefits such as recreation, aesthetic views and air quality, and the global benefits of biodiversity and carbon sequestration.

Projections

Biodiversity loss globally results in welfare losses in the UK. The average willingness-to-pay for biodiversity protection found across UK studies is 0.205% of GDP per capita. By 2050, between 26.5% (high mitigation) and 32.8% (current policies) of habitats and species may be impacted, resulting in welfare losses equivalent to 0.06% of GDP. By 2100, under current policies, the proportion of impacted habitats and species is expected to reach 54.2%, carrying welfare losses of 0.11%.

On the other hand, we find that the value of forests is expected to increase in the UK. This is largely driven by the benefits of CO_2 fertilisation and the projected success of trees under the resulting higher rates of net primary productivity. These changes result in over £1 billion in added ecosystem services by the end of the century, driven mostly by increases in recreational value, followed by land value and carbon sequestration.

In most regions of the UK, losses from biodiversity decline are greater than the gains from forest expansion. However, the high population density and high projected gains in forest cover near Manchester show net benefits for this region (see Figure 3.4).

Table 3.4. Welfare losses from global biodiversity loss (top row) and welfare benefits from expanding forests (remaining rows)

	Current policies (% GDP)			High mitigation (% GDP)			Avoided costs (% points)		
	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected change	1 in 20 more than
Welfare loss from global biodiversity impacts									
2011 – 2030	0.00	0.04	0.10	0.00	0.04	0.11	-0.01	0.00	0.01
2041 – 2060	0.00	0.07	0.17	0.00	0.06	0.15	-0.00	0.01	0.04
2081 – 2100	0.01	0.11	0.26	0.00	0.06	0.15	0.01	0.06	0.13
Total annual benefits (shown negative) from forest gains									
2011 – 2030	-0.023	-0.013	-0.007	-0.021	-0.013	-0.006	-0.007	-0.001	0.005
2041 – 2060	-0.056	-0.035	-0.017	-0.046	-0.024	-0.002	-0.027	-0.012	0.002
2081 – 2100	-0.099	-0.063	-0.021	-0.050	-0.021	0.018	-0.057	-0.042	-0.027
Contributing model results:									
Local annual benefits (shown negative) from forest gains									
2011 – 2030	-0.020	-0.011	-0.006	-0.018	-0.011	-0.005	-0.006	-0.001	0.004
2041 – 2060	-0.047	-0.030	-0.014	-0.039	-0.020	-0.002	-0.022	-0.010	0.002
2081 – 2100	-0.083	-0.053	-0.018	-0.041	-0.018	0.013	-0.047	-0.035	-0.023
Global annual benefits (shown negative) from forest gains									
2011 – 2030	-0.004	-0.002	-0.001	-0.004	-0.002	-0.001	-0.001	-0.000	0.001
2041 – 2060	-0.009	-0.006	-0.002	-0.007	-0.004	0.000	-0.005	-0.002	0.001
2081 – 2100	-0.017	-0.010	-0.002	-0.008	-0.003	0.004	-0.011	-0.007	-0.003

Figure 3.4.a. Expected costs of ecosystem and biodiversity loss by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)

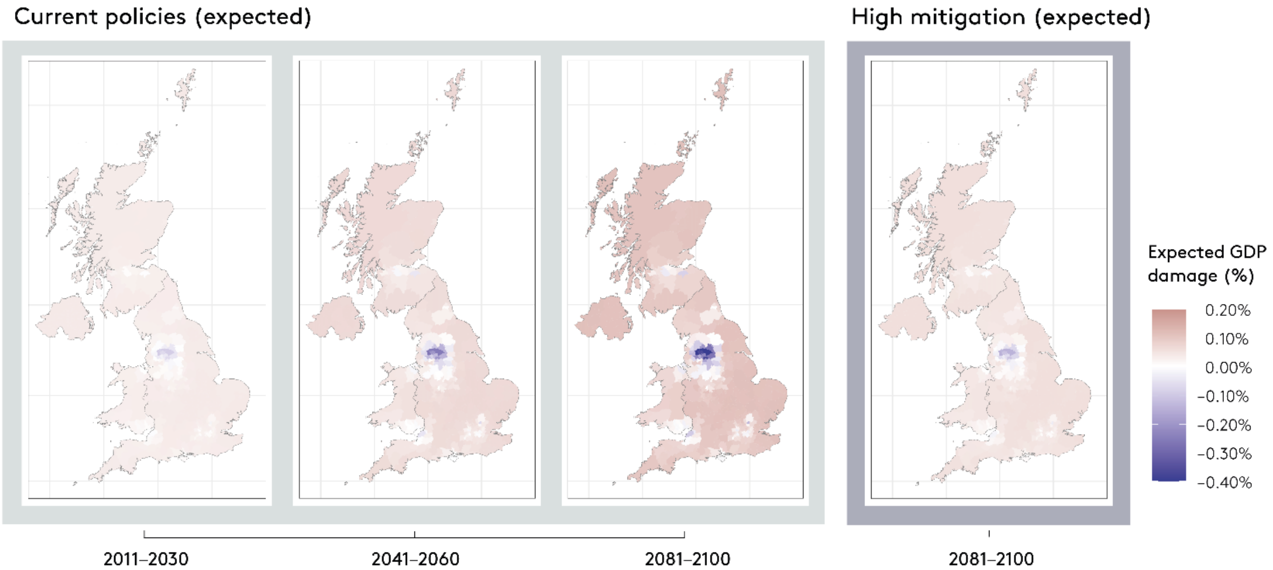
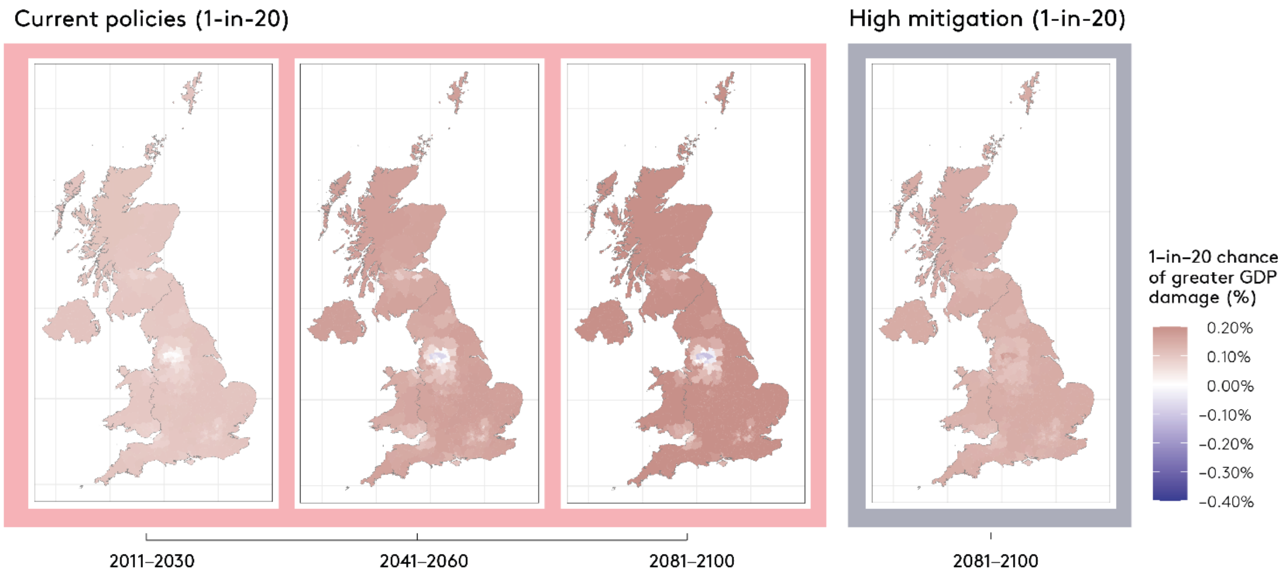


Figure 3.4.b. High-risk costs of ecosystem and biodiversity loss by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)



What we miss

The biodiversity losses used to calibrate our global damages cannot be understood as an unbiased sampling, but they may reflect the losses that humans are most concerned about. We also treat these impacts as biodiversity losses, but in many cases they represent habitat loss even if the species survives in remaining regions, or if they are considered 'committed to extinction', but not yet extinct.

Biodiversity describes a multifaceted outcome of many complex relationships. Land cover alone is a poor proxy for this. While the JULES model accounts for disruption in determining land cover, it does not track the consequences of land cover change for biodiversity. It seems plausible that even as forests expand, the rate of change will undermine the development of the complex relationships that underlie healthy ecosystems. While we predict positive consequences for ecosystem services, the actual results are uncertain.

3.5. Energy supply and demand

Overview

The energy system is expected to see pervasive changes as renewable power expands, the transport system transforms, high-voltage direct current transmission provides new electricity, and local and smart grids change what is possible. Most of the expected changes in the energy system relate to the project of mitigating climate change. However, higher temperatures also have direct impacts on the energy system, reducing production efficiency and increasing cooling demands. Higher summer temperatures can increase the demand for active cooling technologies, such as air-conditioners that run on electricity. Without government intervention to regulate the use of cooling technologies, the UK's annual energy consumption for cooling could almost double between 2020 and 2100 in a 4°C warmer world (AECOM et al., 2021).

Our approach

We rely on two complementary estimates: PESETA IV for electricity production cost changes and Rode et al. (2021) for energy demand changes. Electricity production changes are largely driven by the availability of water, and increased availability may result in cheaper electricity through hydropower. Total energy demand mainly represents the trade-off between the demand for electricity for cooling and the demand for natural gas for heating.

Projections

Total energy demand is expected to decrease with warmer temperatures, reducing costs to the UK economy. However, the increase in energy production costs at the end of the century result in net loss of 0.03% to the UK GDP in 2100.

Table 3.5. Losses from changing costs in electricity production (top rows) and energy demand costs (bottom rows)

	Current policies (% GDP)			High mitigation (% GDP)			Avoided costs (% points)		
	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected change	1 in 20 more than
Electricity production costs from PESETA IV, including CGE effects									
2011-2030	-0.010	-0.004	0.001	-0.010	-0.004	0.001	-0.007	-0.000	0.008
2041-2060	-0.012	-0.003	0.007	-0.011	-0.004	0.003	-0.011	0.001	0.014
2081-2100	-0.015	0.009	0.048	-0.011	-0.003	0.009	-0.016	0.011	0.052
Energy demand costs from Rode et al. (2021)									
2011 – 2030	-0.003	-0.002	-0.001	-0.003	-0.002	-0.001	-0.001	-0.000	0.000
2041 – 2060	-0.005	-0.004	-0.002	-0.005	-0.003	-0.001	-0.002	-0.001	0.000
2081 – 2100	-0.009	-0.006	-0.003	-0.005	-0.002	0.000	-0.005	-0.003	-0.002

Note: Expected values are negative, implying a benefit from climate change.

Figure 3.5.a. Expected costs of energy supply and demand by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)

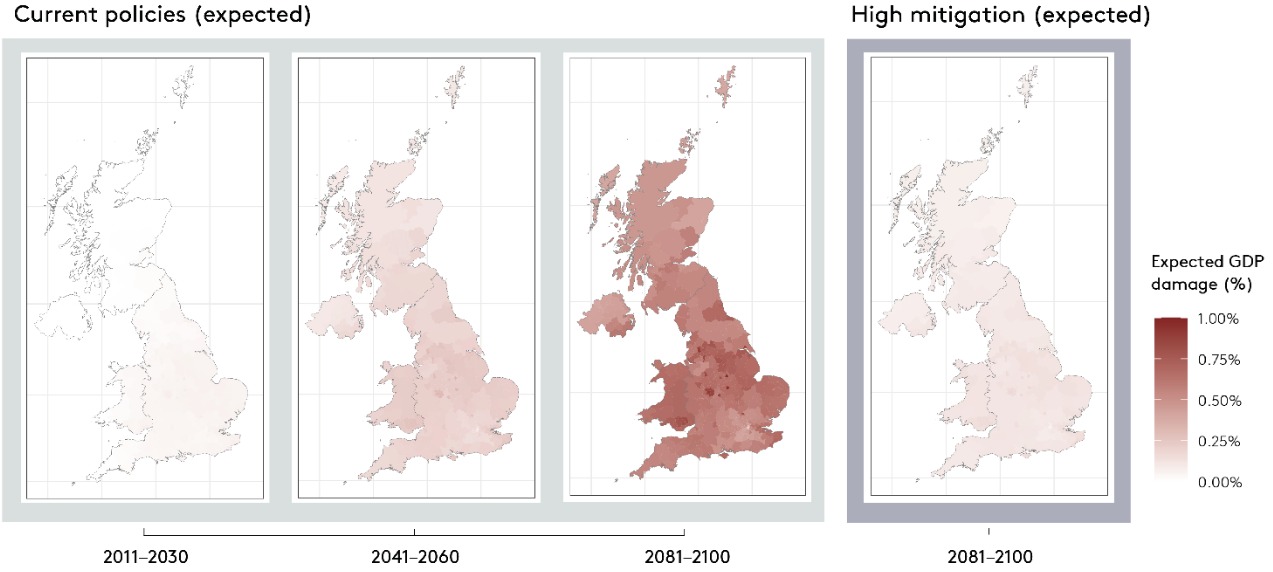
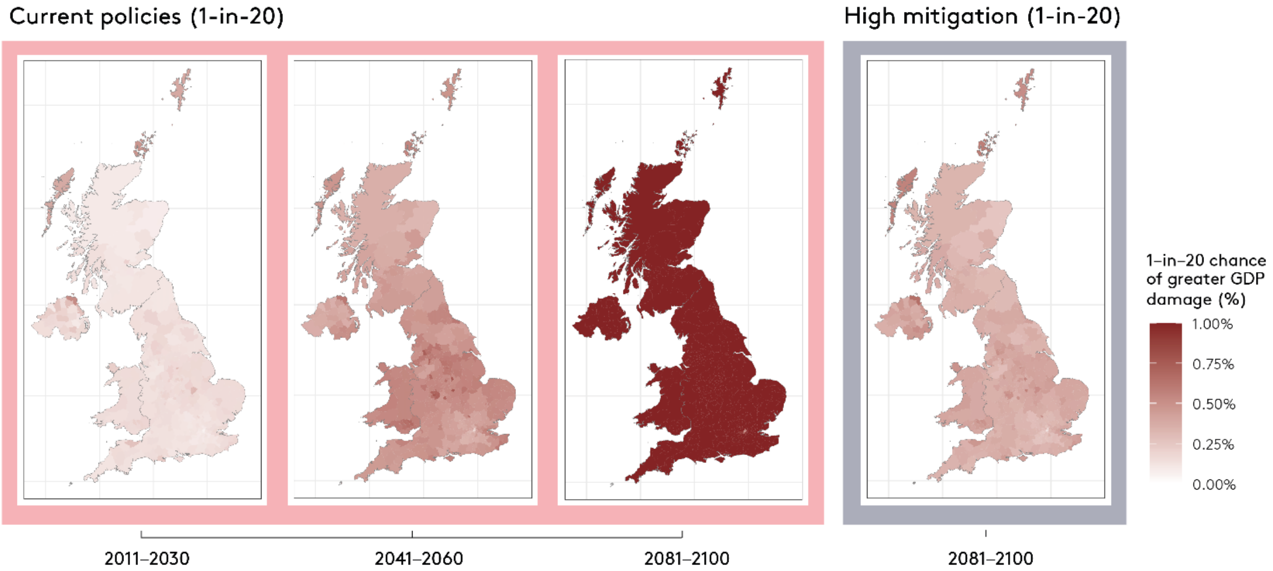


Figure 3.5.b. High-risk costs of energy supply and demand by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)



What we miss

These results assume a static energy system, yet considerable changes are expected over the next century. As the energy system transitions away from thermoelectric power plants, the effects of temperature on electricity production are expected to decrease.

At the same time, energy demand may rise as wealth increases in the future. This effect is removed from the energy demand estimates as it is not driven by higher temperatures, but if energy supply becomes limited, or if other costly policies are put in place to reduce it, the size of the temperature-driven effects could increase. The total decreases in production costs per unit of energy and the complex effects of increases in demand create an unclear effect overall.

3.6. Labour productivity

Overview

When workers are exposed to high temperatures their productivity can be reduced. Beyond a particular threshold, rising air temperature is generally associated with decreasing human performance because temperature affects endurance, fatigue and cognitive performance (Gosling et al., 2018; Houser et al., 2015). High levels of humidity exacerbate the impacts of heat on the human body (Kjellstrom et al., 2016). Outdoor labour productivity is vulnerable to high temperatures and humidity because these workers are more exposed to environmental conditions. Indoor labour productivity can also be impacted by high temperatures and humidity, but generally to a lesser extent because it is easier to control conditions indoors through air-conditioning, for example. In sectors that require physical labour, workers are at greater risk of heat stress because this kind of work generates internal body heat (Houser et al., 2015). Labour productivity is therefore likely to be more negatively impacted by high temperatures in these sectors.

Our approach

We rely on a meta-analysis of five productivity models performed by PESETA III. Each model is represented as an exposure response function (ERF), describing how productivity falls with temperature and humidity.

Projections

Outdoor labour productivity is expected to fall, with some consequences for UK-wide GDP. The relatively small impact reflects both the comparatively cool temperatures in the UK and the high proportion of UK GDP that is driven by the service sector, which is not included in the estimate.

Table 3.6. Economic losses from changes in outdoor labour productivity

	Current policies (% GDP)			High mitigation (% GDP)			Avoided costs (% points)		
	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected change	1 in 20 more than
Annual labour productivity losses, including CGE effects									
2011 – 2030	0.001	0.003	0.006	0.001	0.003	0.005	-0.002	0.000	0.002
2041 – 2060	0.003	0.010	0.020	0.001	0.006	0.014	-0.002	0.004	0.011
2081 – 2100	0.004	0.026	0.055	-0.000	0.006	0.016	0.004	0.020	0.042

Figure 3.6.a. Expected costs of labour productivity by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)

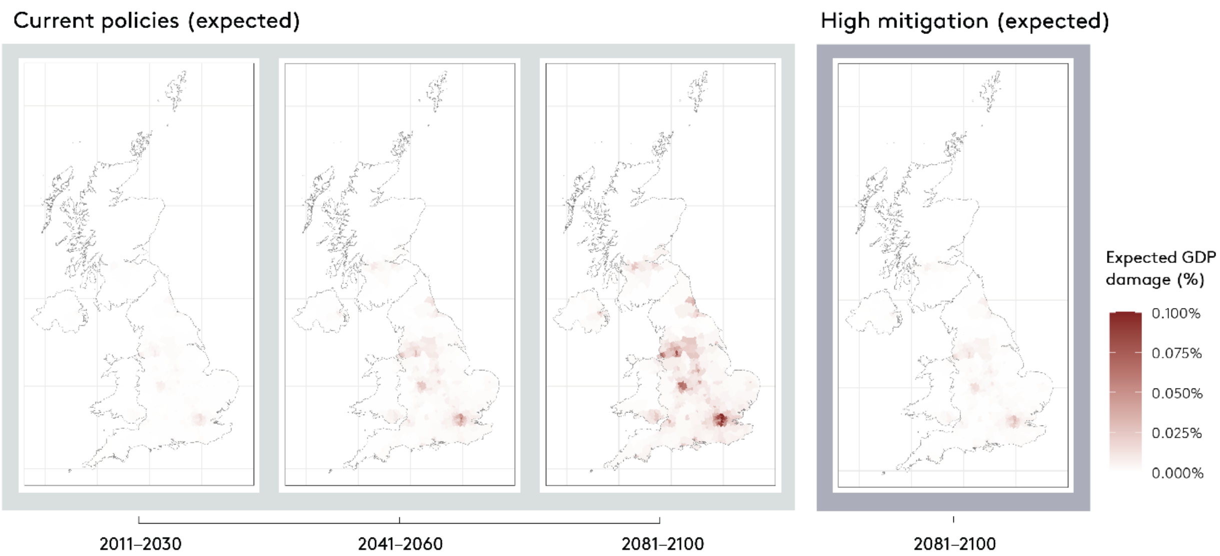
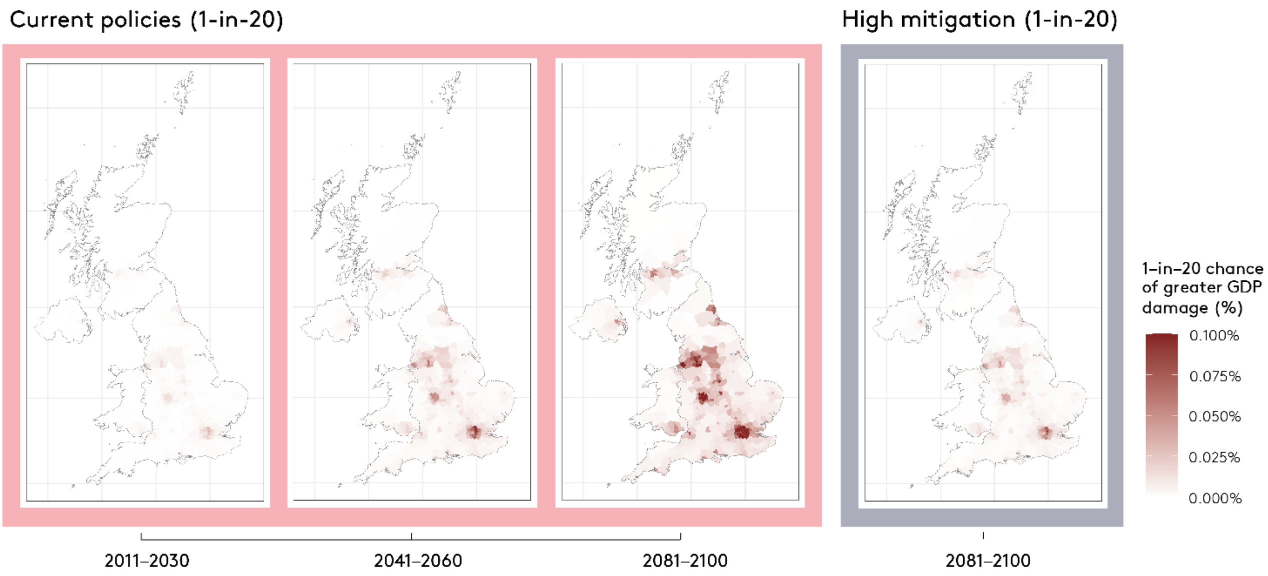


Figure 3.6.b. High-risk costs of labour productivity by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)



Note: The costs shown reflect local economic losses from changes in outdoor labour productivity.

What we miss

While outdoor labour productivity is most directly exposed to higher temperatures, indoor productivity has also been found to be affected (Graff Zivin and Neidell, 2014). Given the larger share of output produced by indoor labour, even small effects on these workers can be significant. In addition, while the traditional approach to damages from labour productivity considers the reduction in sectoral outputs, there are also direct losses to the welfare of workers, and these are expected to be of similar magnitude. Total welfare losses through the labour productivity channel are likely to be considerably greater than we project.

3.7. Health

Overview

The impacts of climate change on mortality and morbidity are among the most economically significant for many countries (Hsiang et al., 2017). Exposure to high temperatures can lead to the development of heat-related illnesses, such as heat exhaustion and heat stroke (Grubenhoff et al., 2007). Without treatment, heat stress can rapidly become life-threatening (Houser et al., 2015). The elderly are particularly vulnerable to heat-related mortality and morbidity. For example, among the estimated 2,500 excess deaths that occurred in England during the three heatwaves experienced in the summer of 2020, the majority were among the 65 and older age group (Public Health England, 2020).

Higher temperatures have also been associated with increases in hospital admissions in England and Wales, amounting to over 12,000 additional admissions per year in recent years. While cold-related issues have decreased, the net change is over 8,000 additional admissions per year (Office for National Statistics, 2022).

Our approach

We apply two complementary models from the literature, both of which aim to project changes in death rates. First, PESETA IV constructed a model of deaths from cold spells and heat waves based on observed relationships across the deaths attributed to these events within each country (Naumann et al., 2020). We use the changes in death rates estimated for UK and Ireland to describe future changes in the UK. Second, Bressler et al. (2021) adapt a comprehensive study on future temperature impacts on mortality by Gasparrini et al. (2017) to describe country-level changes in mortality. Changes in death rates are translated into GDP-equivalent welfare losses using the value of a prevented fatality (VPF), estimated as £1.83 million by the Department for Transport (2016).

Projections

Mortality rates are expected to increase first in southern regions of the UK. Cooler northern regions see a counterbalancing effect for much of the century due to reduced risks of cold-related deaths (see Figure 3.7). According to Bressler et al., these beneficial effects result in fewer deaths even under a current policies scenario. However, the model in Feyen et al. (2020), which looks directly at cold- and heat-related deaths, finds that heat-related deaths are already outpacing cold-related savings today. We treat this disagreement as a form of uncertainty and find that the best estimate of net changes in the mortality rate at end of century is about 7.1 deaths per 100,000 people. This is about twice the death rate from road accidents in the UK. Excess death rate tables are included in Annex G.

Table 3.7. Changes in mortality rate in terms of excess deaths per 100,000 people

	Current policies (% GDP)			High mitigation (% GDP)			Avoided costs (% points)		
	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected change	1 in 20 more than
Best-estimate heat/cold mortality, change in death rate									
2011 – 2030	-0.18	-0.11	-0.04	-0.14	-0.07	0.00	-0.14	-0.04	0.06
2041 – 2060	-0.06	0.08	0.29	-0.15	-0.03	0.16	-0.08	0.12	0.31
2081 – 2100	-0.03	0.40	1.10	-0.19	-0.05	0.16	0.04	0.45	1.08
Contributing model results:									
Bressler et al. (2021), change in death rate									
2011 – 2030	-0.28	-0.23	-0.18	-0.28	-0.22	-0.17	-0.07	-0.00	0.06
2041 – 2060	-0.32	-0.22	-0.06	-0.31	-0.23	-0.07	-0.17	0.00	0.18
2081 – 2100	-0.28	0.09	0.79	-0.31	-0.19	0.08	-0.16	0.28	0.97
Heat/cold mortality from PESETA IV, change in death rate									
2011 – 2030	-0.04	0.10	0.26	-0.04	0.10	0.25	-0.19	0.01	0.21
2041 – 2060	0.03	0.30	0.66	-0.02	0.19	0.47	-0.23	0.11	0.46
2081 – 2100	0.01	0.70	1.76	-0.06	0.18	0.52	-0.17	0.52	1.45

Notes: Mortality rates according to the model by Bressler et al. (2021) (top rows), PESETA IV (middle rows), and a combination that applies information from both (bottom rows).

Figure 3.7.a. Expected costs of climate change on health by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)

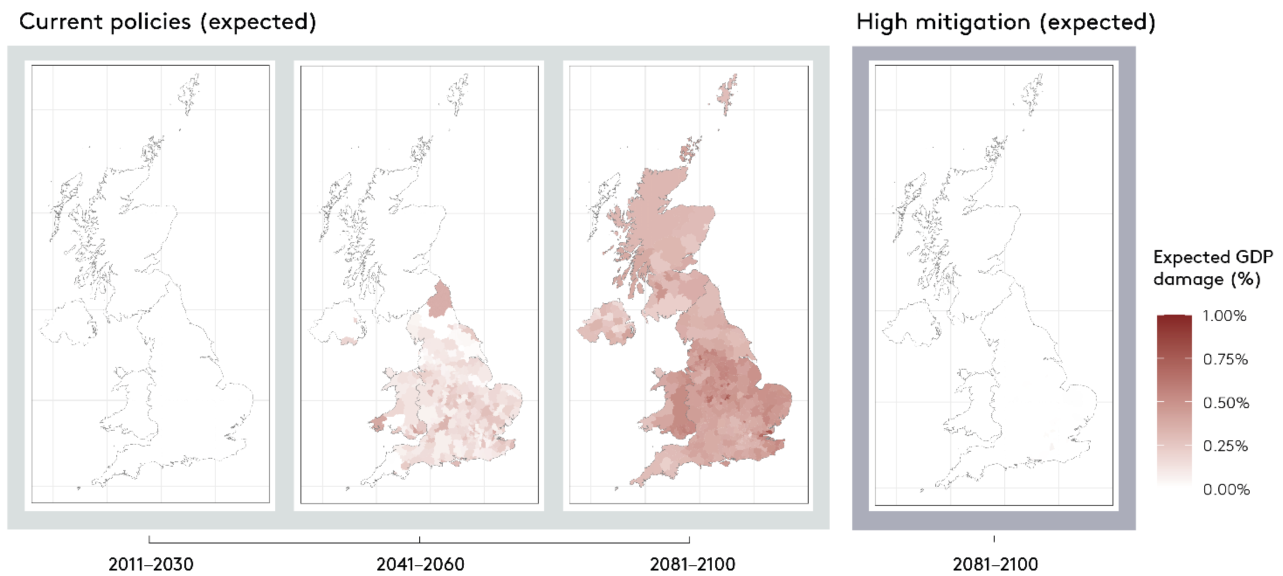
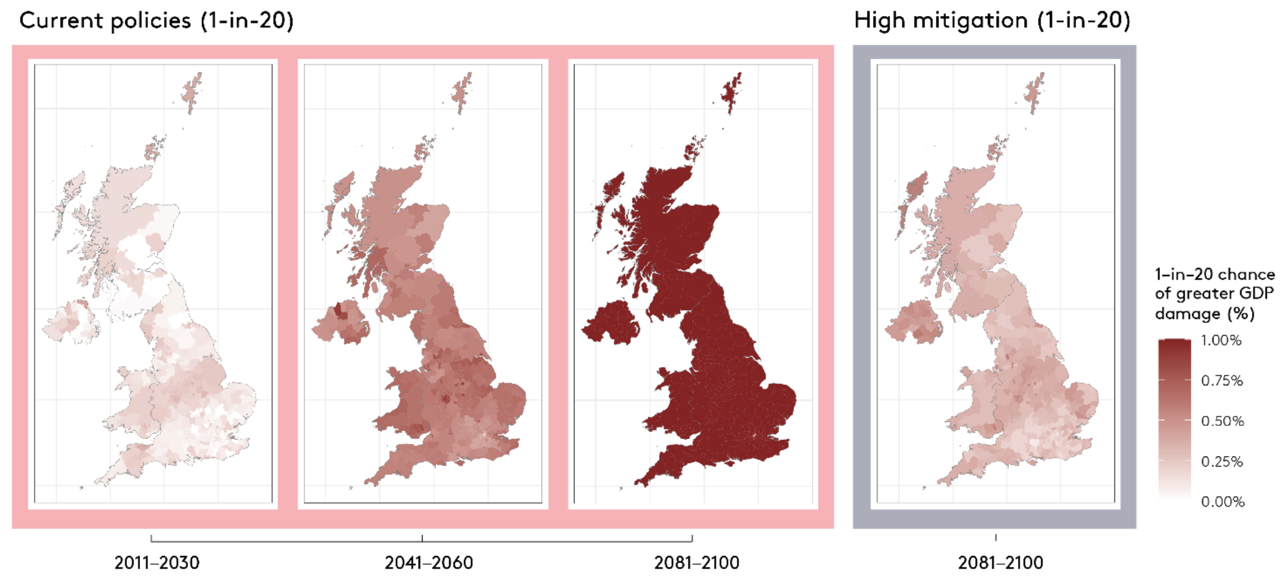


Figure 3.7.b. High-risk costs of health by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)



Note: The costs shown reflect losses to welfare due to increased risk of death from changing temperatures.

What we miss

These results consider only the effect of climate change on mortality, but morbidity and hospitalisation may be the greater concern given that non-fatal health problems are so much more prevalent. For every death that occurs there are many more hospitalisations, and for every hospitalisation there are many cases of diseases that do not involve medical professionals but result in losses to welfare and productivity. To illustrate, there were 6 million emergency hospital visits in England in 2017/18, compared with about 600,000 deaths in England and Wales within the same period (Steventon et al., 2018; Statista, 2022b).

Some diseases will also become more common with climate change if they depend on a species or vector whose range is affected by temperatures. Several of these 'vector-borne' diseases are expected to expand within the UK (Semenza and Suk, 2018). Violent crime (not considered in this report) is also expected to increase with temperatures, with possible effects on mortality and health. Total losses to welfare through the health channel are likely to be greater than we project.

3.8. Coastal impacts

Overview

The UK has 12,429 km of coastline, with 3.2 million people occupying areas at risk of annual coastal flooding (Kulp and Strauss, 2019). Under climate change (in which temperatures increase by around 4.3°C by 2100), this risk could expand to areas currently occupied by 5.4 million people. Beyond the risk to properties and communities, coastal flooding also poses a risk to infrastructure, farmland and natural habitats. For example, infrastructure across the UK, including 35 power stations, 22 clean water facilities and 91 sewage treatment works, are located in areas at significant risk from coastal flooding (UK Climate Risk, 2021). Transport infrastructure situated close to the coast is likely even more vulnerable to coastal flooding because it is more difficult to protect the full length of rail lines and roads (ibid.).

Despite these risks, there are many opportunities for adaptation, ranging from creating new infrastructure to engaging in concerted efforts to retreat from the current coastline. The recent increase in the use of the Thames Barrier, driven both by local sea-level rise and more intense storms, highlights the importance of having and deploying these kinds of protections against climate change impacts.

Our approach

We rely on CIAM, a sophisticated engineering-economic model of coastal risks and adaptation (Diaz, 2016). This model can reflect 'optimal' coastal policies, where foreseen risks are minimised through adaptation actions. In the absence of evidence about the level of adaptation that will actually be observed, we treat this as a form of uncertainty.

Projections

CIAM reports damages from inundation, storm surges, wetland loss, relocation costs and protection costs. By the end of the century, total direct damages reach 0.46% of GDP and equilibrium effects within the economy (estimated as increasing total losses by 22%) exacerbate this loss to 0.56%. The damage depends on the level of adaptation, with the vast majority of losses occurring where adaptation is limited. The projected economic costs in the absence of adaptation are £24.75 billion per year in 2050, while optimal adaptation reduces this to £3.41 billion. Storms and the cost of relocation contribute the largest share of costs. Losses in billions of pounds are reported in Annex I.

Table 3.8. Components of UK-wide costs from coastal impacts and adaptation costs

	Current policies (% GDP)			High mitigation (% GDP)			Avoided costs (% points)		
	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected change	1 in 20 more than
Total damages from coastal impacts									
2011 - 2030	0.048	0.194	0.435	0.046	0.190	0.444	-0.136	0.004	0.142
2041 - 2060	0.049	0.305	0.821	0.037	0.228	0.660	-0.197	0.077	0.484
2081 - 2100	0.036	0.460	1.237	0.021	0.206	0.692	-0.005	0.253	0.928
Contributing model results:									
Inundation losses from coastal impacts									
2011 - 2030	0.025	0.066	0.137	0.024	0.066	0.140	-0.042	0.001	0.041
2041 - 2060	0.027	0.081	0.177	0.022	0.061	0.138	-0.020	0.020	0.089
2081 - 2100	0.016	0.059	0.115	0.012	0.032	0.064	0.001	0.027	0.073
Storm losses from coastal impacts									
2011 - 2030	0.002	0.010	0.024	0.002	0.009	0.026	-0.011	0.001	0.011
2041 - 2060	0.002	0.080	0.290	0.002	0.068	0.260	-0.137	0.012	0.190
2081 - 2100	0.003	0.268	0.889	0.004	0.140	0.552	-0.135	0.128	0.673
Wetland losses from coastal impacts									
2011 - 2030	0.001	0.005	0.010	0.001	0.005	0.009	-0.005	0.000	0.006
2041 - 2060	0.003	0.012	0.026	0.000	0.007	0.016	-0.009	0.005	0.021
2081 - 2100	0.005	0.017	0.030	-0.000	0.003	0.008	0.002	0.014	0.028
Relocation costs from coastal impacts									
2011 - 2030	0.006	0.107	0.270	0.007	0.106	0.276	-0.086	0.001	0.087
2041 - 2060	0.007	0.134	0.336	0.005	0.090	0.252	-0.025	0.043	0.187
2081 - 2100	0.004	0.086	0.191	0.002	0.037	0.093	0.002	0.049	0.134
Protection costs from coastal impacts									
2011 - 2030	0.000	0.007	0.016	0.000	0.007	0.016	-0.003	0.000	0.004
2041 - 2060	0.000	0.006	0.014	0.000	0.004	0.011	-0.001	0.001	0.006
2081 - 2100	0.000	0.003	0.008	0.000	0.002	0.006	0.000	0.001	0.005

Note: Coastal impacts (or risks) include inundation, storm surges and wetland losses. Adaptation costs include relocation and protection costs.

Figure 3.8.a. Expected costs of coastal impacts (losses and adaptation costs) by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)

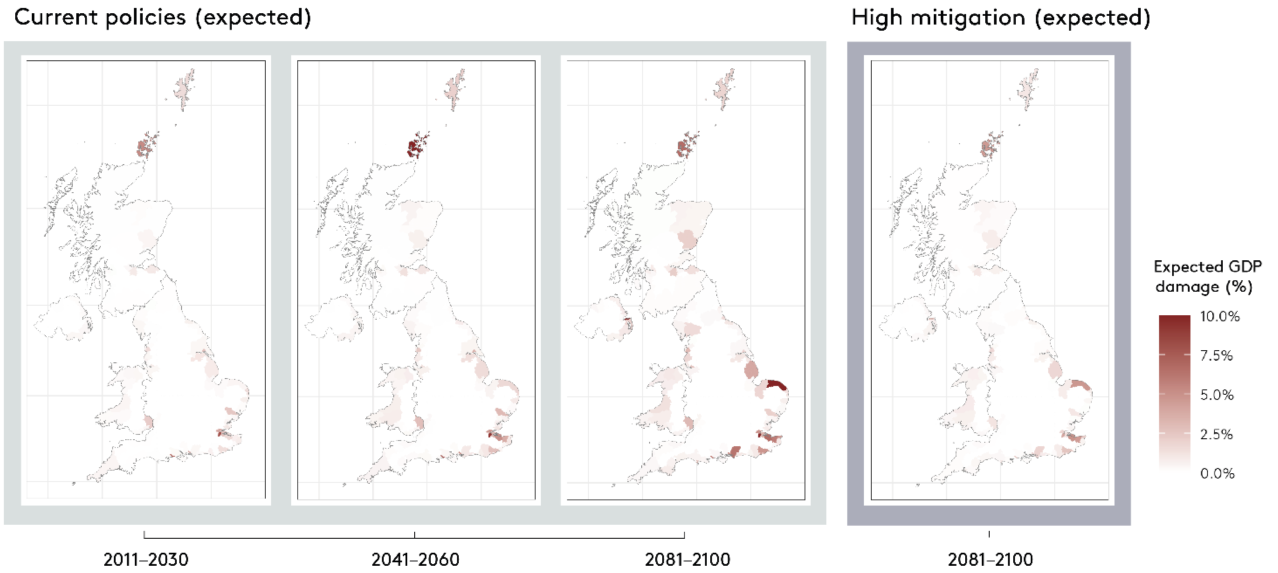
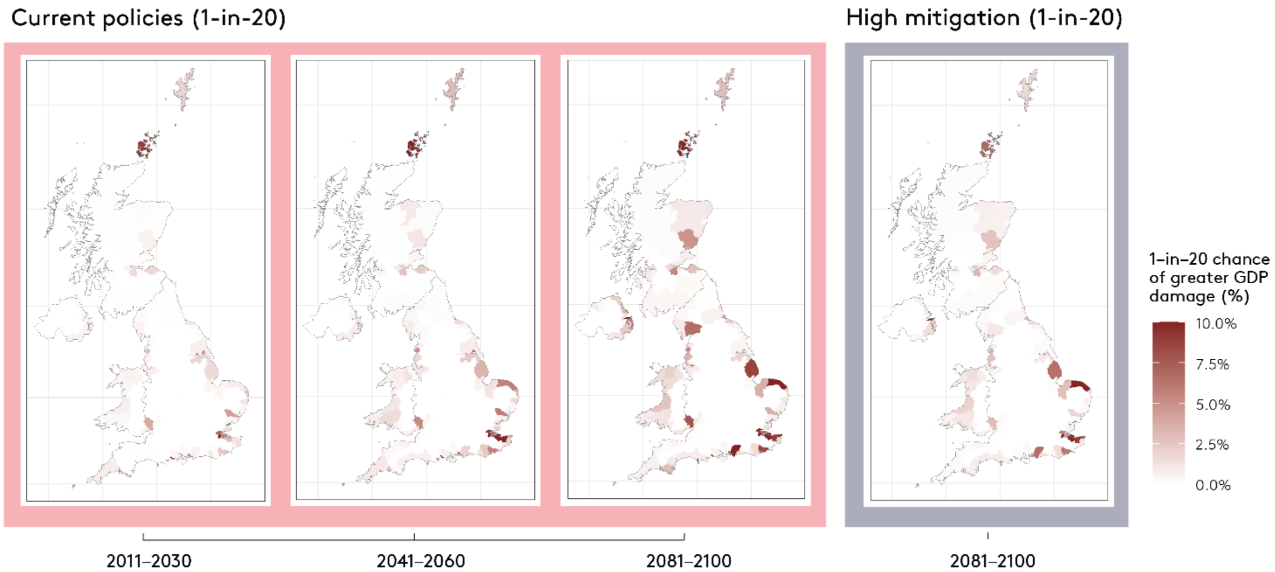


Figure 3.8.b. High-risk costs of coastal impacts (losses and adaptation costs) by region of the UK, 2011–2100, under current policies and high-mitigation scenarios (% of local GDP)



Note: Only coastal counties with losses are shown.

What we miss

The value used to calculate the cost of land lost to sea level rise and flooding is based on an estimate of the value of land and on capital losses. This is an underestimate of the wider value of living in coastal communities to the people who have chosen to live there.

Many coastal impacts are expected to occur due to large storm events. While our methodology captures the direct losses from storm surge inundation, these events can have far-reaching consequences by disrupting regional transport and supply chains. When whole communities are impacted, relief is not always readily available. There is also evidence that large storms have long-lasting effects, with communities not returning to their previous economic trajectory for at least 20 years (Hsiang and Jina, 2014). In the absence of strong policies for proactive adaptation (coastal protections and managed retreat), coastal damages from increasing storms could be very high.

3.9. Trade effects

Overview

While the UK benefits from a temperate climate, much of the rest of the world will experience considerable losses from even small increases in temperature. It is reasonable to expect, however, that the UK will not be isolated from these wider impacts as it will likely experience losses in trade, increases in migration, and other geopolitical consequences as 'spillover' effects from climate change globally. In the agricultural sector, for example, the UK imports large quantities of fruit and vegetables from countries that will suffer serious impacts from climate change: 3.8% of this produce comes from highly climate-vulnerable countries such as Belize and India and 13.8% from moderately vulnerable countries such as South Africa and Brazil (Parliamentary Office of Science and Technology, 2019).

Our approach

We use estimates of how temperatures impact GDP from Dell et al. (2012), Burke et al. (2015) and Kahn et al. (2021), reflecting a range of results from an innovative new literature. To translate these into consequences for the UK, we use existing import and export flows, scaling these according to the losses in other countries. We then use the results of previous computational general equilibrium (CGE) modelling of the impacts of import and export changes on GDP, which are drawn from studies of Brexit trade scenarios. Finally, we combine the three loss estimates into a best estimate.

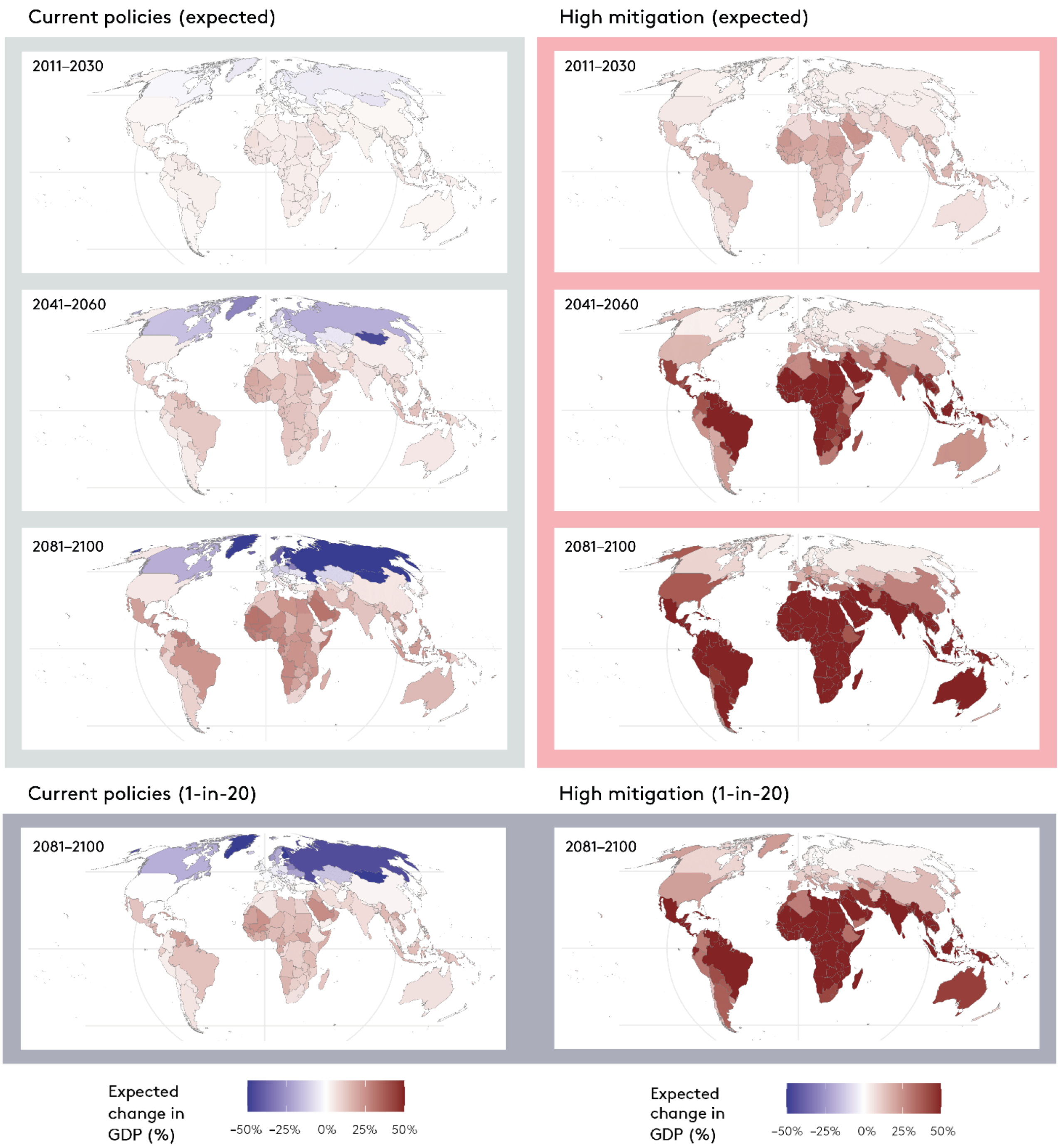
Projections

The best estimate of losses through trade effects is about 1.1% of UK GDP by 2100. This is based on the three models described above, which hold very different estimates. Dell et al. find that poor countries are mainly at risk, and we follow their lead by modelling impacts for only the countries below the median GDP. This results in the smallest of the three impact estimates. Burke et al. (2015) argue that the persistent losses in economic growth accumulate indefinitely. This scenario produces the largest effects, with some countries' economies being decimated by climate change.

Table 3.9. Losses to GDP from 'spillover' effects due to climate change risks

	Current policies (% GDP)			High mitigation (% GDP)			Avoided costs (% points)		
	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected	1 in 20 more than	1 in 20 less than	Expected change	1 in 20 more than
Best-estimate of trade losses									
2011 - 2030	0.06	0.27	0.54	0.05	0.28	0.58	-0.26	-0.00	0.23
2041 - 2060	0.02	0.61	1.49	-0.05	0.51	1.34	-0.50	0.10	0.71
2081 - 2100	-0.28	1.11	3.17	-0.34	0.64	2.06	-0.77	0.47	1.85
Contributing model results:									
Trade losses derived from Dell et al. (2012)									
2011 - 2030	0.01	0.02	0.04	0.01	0.03	0.04	-0.00	-0.00	-0.00
2041 - 2060	0.02	0.05	0.08	0.02	0.04	0.07	0.00	0.01	0.01
2081 - 2100	0.04	0.09	0.14	0.02	0.05	0.08	0.02	0.04	0.06
Trade losses derived from Burke et al. (2015)									
2011 - 2030	-0.70	0.26	1.19	-0.73	0.28	1.21	0.03	-0.02	-0.02
2041 - 2060	-3.11	1.04	4.32	-3.11	1.00	4.10	0.00	0.04	0.22
2081 - 2100	-10.22	2.09	8.48	-8.35	1.43	6.80	-1.87	0.66	1.67
Trade losses derived from Kahn et al. (2021)									
2011 - 2030	0.11	0.28	0.49	0.11	0.29	0.52	-0.00	-0.00	-0.03
2041 - 2060	0.09	0.27	0.48	-0.04	0.08	0.23	0.13	0.19	0.25
2081 - 2100	0.09	0.26	0.48	-0.10	-0.01	0.14	0.18	0.28	0.35

Figure 3.9. Expected and high-risk loss of GDP per capita due to climate change by country, illustrating potential spillover costs to the UK through trade, 2011–2100, under current policies and high-mitigation scenarios



What we miss

New research suggests that temperature variability and the hydrological cycle also have top-down impacts on GDP (Kotz et al., 2021; 2022). These are not included in our estimates and more work is needed to properly represent them without double-counting risks, but they are expected to be important drivers of risk. There is currently considerable disagreement across the research on top-down economic risks, with total effects varying to a significant degree (Piontek et al., 2021). More work is needed to understand whether these values are likely to be an overestimate or an underestimate.

3.10. Additional impact channels

The list of climate change impact channels included in this report is expansive but not exhaustive. To make it more comprehensive, the following channels could be included: natural disasters, tourism, forestry, transport, conflict and displacement. It is important to deal with these from a policy perspective, even if they cannot be precisely quantified (Smith and Stern, 2011). We provide brief explanations of what is known about how climate change impacts each of these below.

The net result of these omissions, along with what is noted in the 'What we miss' parts of the channel analysis sections above, is that the results presented in the report are conservative, lower-bound estimates of the costs of climate change to the UK. It seems likely that some of these missing channels will emerge as disruptive and costly. Proactive adaptation can certainly reduce the losses (our estimates generally assume a low level of adaptation), and the total losses may fall below our projections, particularly if new opportunities for adaptation are embraced.

Natural disasters

The cost of damages from windstorms across the UK is expected to increase, from £444 million per year between 1981–2010 to £463 million under 1.5°C of warming (PESETA IV). This is a modest increase, but the dynamics of windstorms need to be better understood to provide proper uncertainty bounds. There will also be a greater number of days with a high danger of wildfires in southern England. Translating this change into economic and welfare losses is an important task. The risk of extreme extratropical storms is also expected to increase in many regions.

Tourism and recreation

Tourism is one of the important sectors in the UK, contributing £237 billion (or about 11%) to GDP in 2019. Tourist destinations in upland areas of Scotland and in coastal areas are particularly vulnerable to climate change. In Scotland, winter sports and skiing are at risk from warming temperatures. Rising sea levels are resulting in increased sedimentation or loss of sandy beaches in some locations, including parts of Wales, impacting tourism. The related sector of recreation will also be impacted.

Forestry

The valuation of ecosystem services from forests (Section 3.4) did not include the sale of wood. In the UK, around 319,000 hectares of land is covered by forest (FAO, 2020). Forests can reduce the impact of climate change by absorbing carbon dioxide and storing carbon in leaves, twigs, trunks and soil. However, rising temperatures and changing precipitation patterns may disturb the practice of silviculture as trees will grow better in some areas but decline in others. In the light of such changing circumstances, forest planning management in the UK can build resilience against the uncertainties presented by climate change.

Transport

Transport accounts for 27% of UK's total emissions (FAO, 2020), but transport systems are also at risk from climate change. Precipitation, changes in wind speed and extreme temperatures can all affect transport. For example, the economic costs to the transport sector from the 2015 and 2016 UK floods in the totalled £121 million for rail and £220 million for road (Environment Agency, 2018a). A 2006 paper estimated travel disruption due to flooding in London to cost approximately £100,000 per hour during peak periods for each main road affected (Arkell and Darch, 2006).

Crime and conflict

Violent crime and civil conflict have both been shown to be connected to the incidence of extreme temperatures and rainfall (Carleton et al., 2016). The mechanisms for this effect are still being understood, but in some cases, hunger and loss of productive agricultural work are likely to blame. It also appears that cognitive performance in general is impaired in high temperatures, and this may play a role (Künn et al., 2019; Heyes and Saberian, 2019).

Displacement and refugees

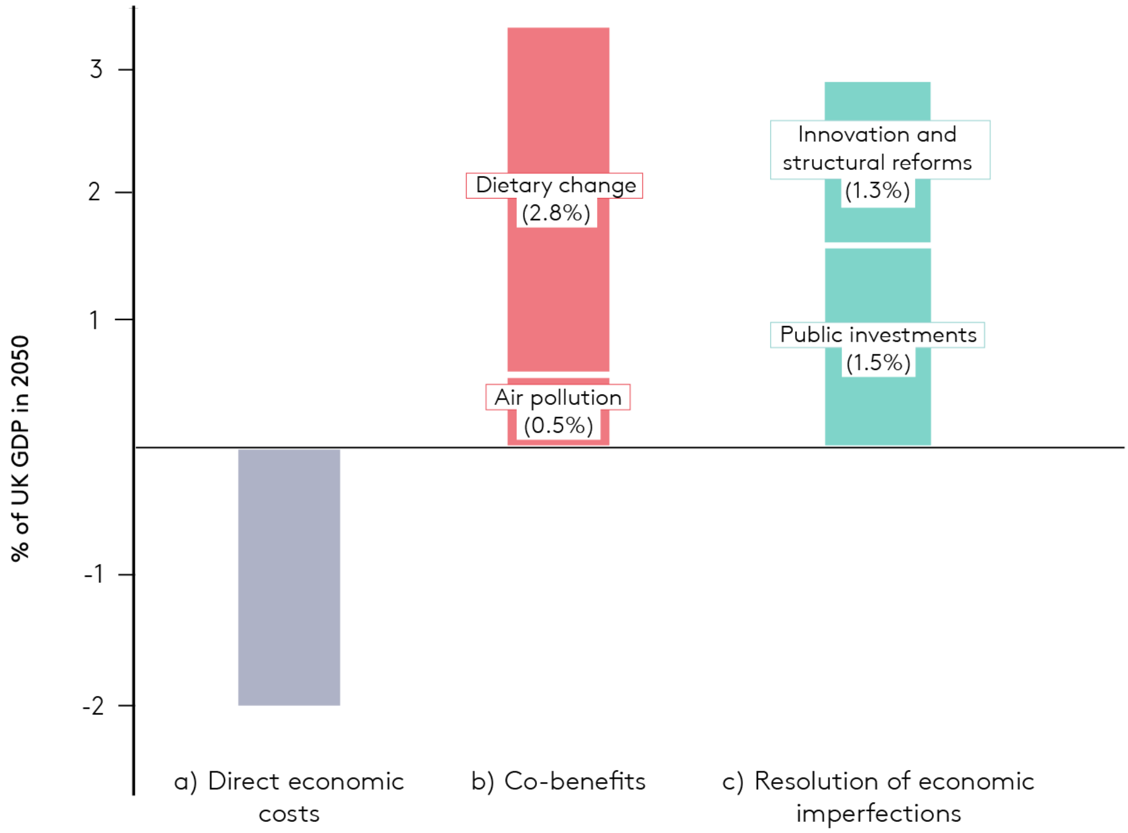
It is likely that climate change is already producing climate refugees across the globe. Xu et al. (2020) show that over the coming 50 years, between one and three billion people could be displaced from their historical environment. While the reactions of different groups to these environmental changes are likely to be complex, there is evidence that asylum applications increase with warming (Missirian and Schlenker, 2017). Under a high warming scenario, asylum applications to the EU are projected to increase 188% by 2100 relative to 2000–2014.

4. Cost comparison of mitigation scenarios and the pathway to net-zero

Overview

In this section, we contrast the damages analysed in earlier parts of the report with the various costs and co-benefits of transitioning to net-zero. Our goal is not to conduct a formal cost-benefit analysis, but to show the relative significance in terms of GDP of the different factors that may influence societal decisions.

Figure 4.1. The annual costs and benefits of the net-zero transition for the UK (other than avoided damages) in 2050 (% of GDP)



Note: Inspired by Köberle et al. (2021).

Figure 4.1 summarises the aspects that we can quantify, albeit subject to many sources of uncertainty. It shows, in terms of percentage of UK GDP in 2050, our best estimates of the various quantifiable economic annual costs of the transition to net-zero. These are grouped into three main categories:

a. The direct economic cost of mitigation
b. The monetisable co-benefits
c. The pro-growth impacts that well-designed net-zero investment and innovation policies can have on the UK economy.

We analyse two very different measures of direct economic costs, which yield similar estimates. The first describes the resource costs of the full portfolio of abatement measures needed to reach net-zero from the UK's Climate Change Committee (CCC). The second corresponds to the macroeconomic costs of climate policies (in particular, the price of carbon) compatible with keeping warming under 2°C, as quantified by integrated assessment models.

The monetisable co-benefits relating to air pollution and dietary change are dominated by the health benefits (in terms of reduced mortality), but also include productivity benefits. The third column in Figure 4.1 corresponds to the positive impact that investments in new infrastructure, technology and skills can have on the UK economy. As the economy is operating below its growth potential due to insufficient investment (van Ark and Venables, 2020), the additional investments driven by the net-zero transition are likely to have considerable benefits.

The exact numbers are subject to a great deal of uncertainty. However, the rough magnitudes seem robust across studies and models. The direct cost of transitioning to net-zero has consistently been estimated to lie between 1% and 2% of GDP, depending on the speed of the transition, and with some sensitivity around the need for and long-running costs of carbon removal technologies. The health co-benefits are sizeable (albeit sensitive to the monetary value of lives saved). The health benefits of dietary change – especially from the reduction in meat consumption – are large, but rely on wide public behavioural change, which is often hard to achieve. The feasibility of such demand-side policies is therefore more uncertain.

The most uncertain numbers are those concerning the macro-economic benefits of a pro-growth net-zero transition. Several models indicate that they outweigh the direct costs of mitigation, leading to a positive net impact of the net-zero transition on the economy, without even accounting for avoided damages and co-benefits. However, whether mitigation investments successfully spur growth depends heavily on the details of policy design (see OECD, 2017).

4.1. Direct costs

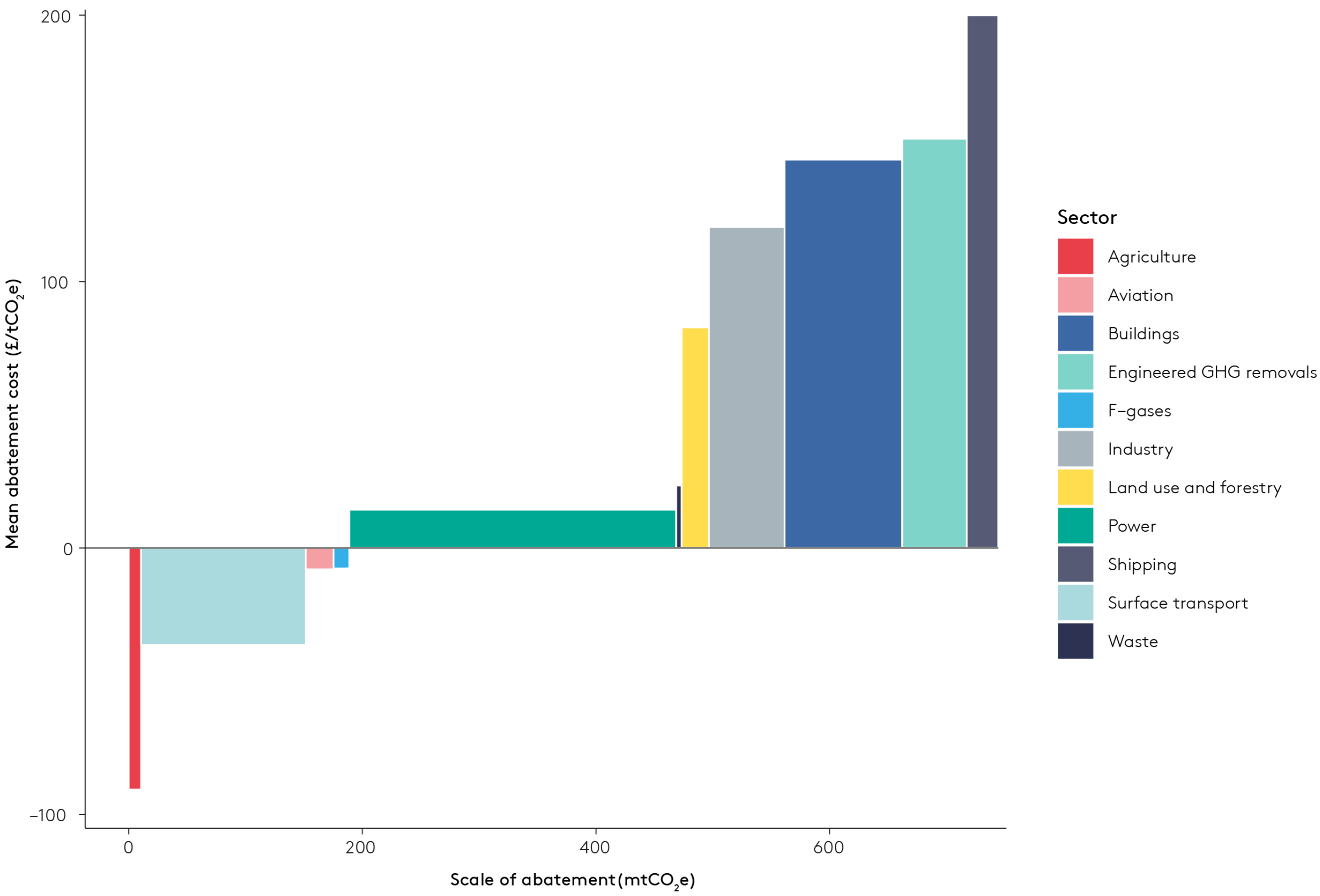
The Climate Change Committee conducted a bottom-up sector-by-sector analysis of the mitigation measures that can, and must, be deployed to reach 100% emissions reduction by 2050 (relative to 2017, the legislated target). For each sector, Figure 4.2 below shows the mean annual cost of deploying available mitigation technologies and processes in that sector and the number of $MtCO_2e$ (megatonnes[3] of CO_2 equivalent) that can be cut as a result.

The resource costs are equal to the capital and operational costs minus the equivalent costs in a scenario using incumbent technologies. These costs are then annualised. On the supply side, there are extensive mitigation measures, including:

- Electrification of heat and transport and a major expansion of low-carbon power generation.
- Development of a hydrogen production (natural gas reformation with carbon capture and storage [CCS]) and a distribution system that will service demand in peak periods and for energy-dense applications such as freight, shipping and industry.
- Carbon capture and storage in industry.
- Land-use change with a shift to agricultural techniques that sequester more carbon and one-fifth of UK agricultural land being reallocated from livestock to tree planting, energy crops or peat restoration.

[3] 1 megatonne = 1 million tonnes.

Figure 4.2. Costs of reaching net-zero emissions by sector across the range of necessary mitigation measures



Source: CCC (2019).

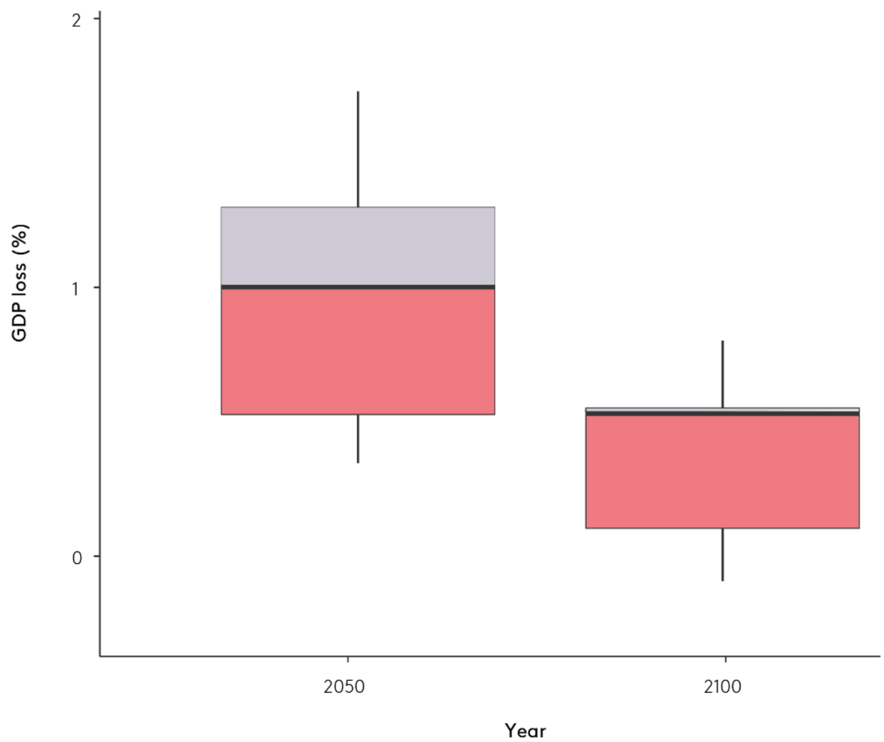
The net-zero scenario also includes a reduction in energy demand. This includes increased energy efficiency of products and processes (including building insulation), as well as a 10% reduction in emissions driven by changes in consumer behaviour (specifically, a 20% reduction in meat consumption and a 5% shift in travel from cars to other modes, both of which do not entail resource costs). If all these measures are deployed, the CCC estimates there will remain 55 $MtCO_2e$ of residual emissions (mostly from agriculture and aviation). These will have to be compensated by engineered greenhouse gas removal (specifically, using wood in construction, bioenergy with carbon capture and storage [BECCS] and direct air capture with carbon storage [DACCS]). As these carbon removal techniques are not yet well-used or evidenced, the CCC has made very conservative cost estimates, for example that DACCS will cost £300/tCO_2e.

A key finding of the CCC is that the costs of mitigation have greatly decreased in the 14 years since the Climate Change Act was passed. In 2008, the Act mandated an 80% emissions reduction relative to 1990, expected to cost 1–2% of GDP per year. The CCC estimates that an 80% reduction is now achievable at the small cost of 0.3% of GDP. This improvement is thanks to innovation-led reduction in costs of some key technologies (particularly wind, solar and batteries). As shown in Figure 4.2, mitigation costs in some sectors are expected to be very low – or even negative. This is the case for surface transport, where electric passenger vehicles are expected soon to be cheaper than conventional vehicles, and in the power sector, where the high costs of supplying hydrogen for peak demand will be offset by the very low operational costs of renewable energy. Given this historical experience, the CCC's estimates include some cost reduction for a number of technologies, but these are conservative and do not assume any breakthroughs. For example, by 2050, the cost of electric vehicles is projected to reduce by 40%, wind and solar costs are expected to further reduce by 25% and 13% respectively, yet the costs of CCS are not expected to decrease.

Macroeconomic cost estimates from integrated assessment ensemble models

The resource costs described above do not include the costs of adjustment to economic activities arising from structural change in the economy and from carbon pricing. Several integrated assessment models have been constructed to estimate global and regional mitigation costs, emissions pathways and associated land use and energy system transition characteristics. These models often have different underlying modelling structures and may differ in some core assumptions about how the macroeconomy adjusts to policy scenarios. In this way, as in climate science, we look at ensembles of models to assess modelling uncertainty. Here, we gather evidence from the database of model and scenario ensembles developed for the Network for Greening the Financial System (NGFS) (Bertram et al., 2021), which have been downscaled to the national level, and the model and scenario ensembles of the ENGAGE consortium (Riahi et al., 2021), which provide up-to-date estimates for the EU as a whole (which we can consider reasonably similar to the UK).

Figure 4.3. Macroeconomic costs of achieving net-zero in the UK



Notes: The distribution of costs is expressed as the percentage of GDP lost in the 'high mitigation' scenario relative to the 'current policies' scenario, as calculated by eight different models for 2050 and 2100. The underlying model results are shown in Annex K.

Figure 4.3 shows the distribution of UK mitigation costs consistent with a high-mitigation scenario, as predicted by eight models from the NGFS and ENGAGE ensembles for 2050 and 2100. It shows a strong degree of agreement across models that the annual cost to GDP in the UK as a result of the country's net-zero transition (without accounting for avoided damages) lies between 0.5% and 2.5% of GDP. The costs come down after 2050, and in 2100 are expected to lie between -0.25 and 1% of GDP. Some models predict low or even negative costs because they assume that the economy is currently not operating at full capacity. Investments in the net-zero transition can therefore stimulate the economy – something that we return to in our discussion of indirect macroeconomic benefits (Section 4.3).

In summary, it is unlikely that the cost of policies to achieve net-zero by 2050 for the UK would exceed 2% of GDP (or approximately £40 billion annually).

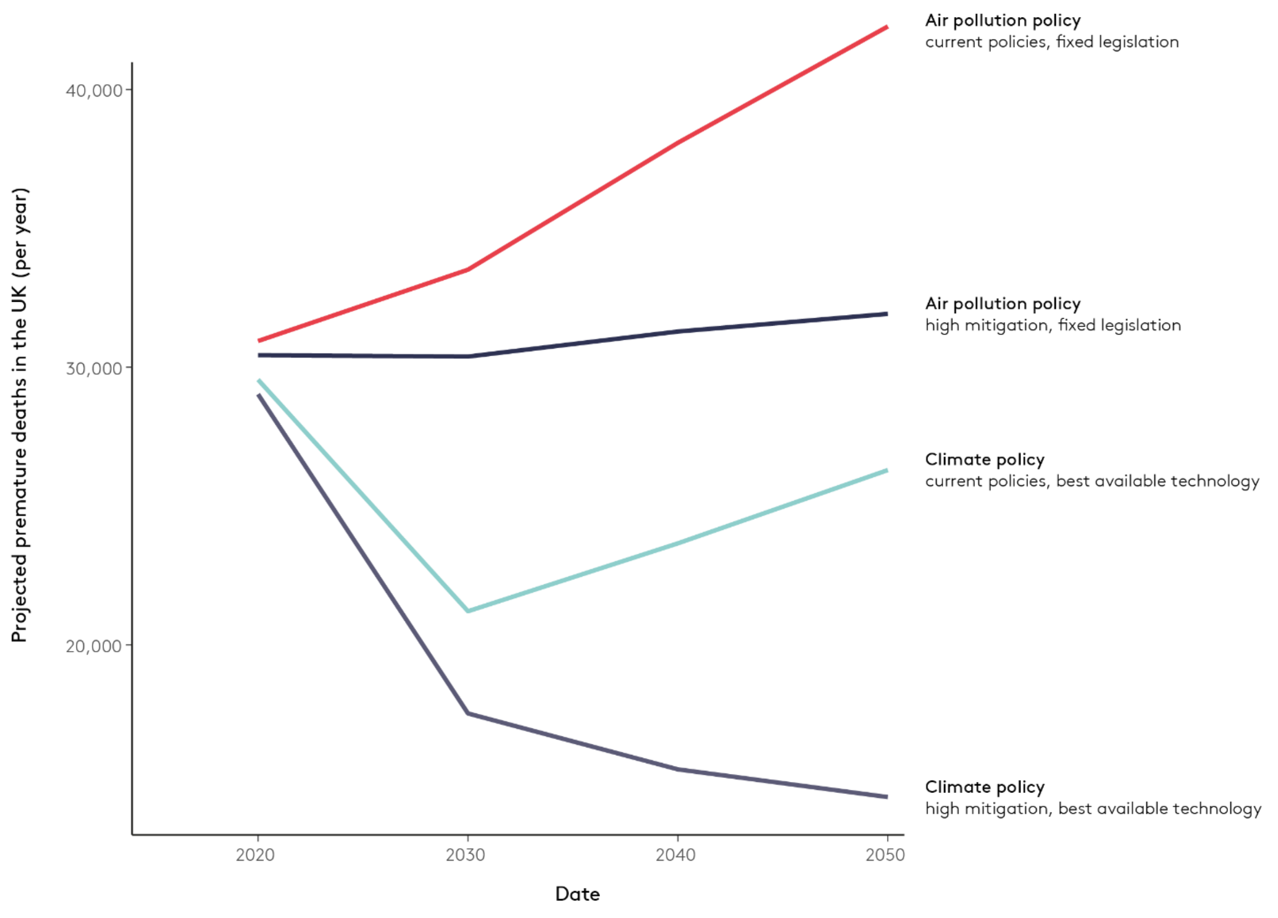
4.2. Co-benefits of climate mitigation

Researchers have recognised a wide variety of co-benefits to climate change mitigation (Karlsson et al., 2020). These range from improved health and productivity to ecosystem services, affordability, comfort and macroeconomic effects. Here we provide quantitative estimates of health co-benefits (in relation to air pollution and diet), which are the best studied, and review examples of ecosystem service benefits relevant to the UK. Section 4.3 considers the macroeconomic benefits.

Air pollution

Globally, ambient air pollution killed 4.2 million people in 2016 and cost humanity 103 million disability-adjusted life years (Cohen et al., 2017). Air pollution and climate change share many of the same drivers (e.g. fossil fuel combustion and livestock farming), and greenhouse gases intersect with air pollutants (e.g. methane is a precursor to ground-level ozone; black carbon is a greenhouse gas and contributes to particulate matter [$PM_{2.5}$]). In this way, many of the mitigation measures that need to be deployed in a transition to net-zero also lead to a substantial reduction in the emission of air pollutants.

Figure 4.4. Changes in premature mortality through pollution and climate policy in the UK



Source: Adapted from Vandyck et al., (2018).

No existing study estimates the health improvements that the UK would experience if it implemented each of the mitigation measures involved in the CCC's net-zero plan (see Section 4.1). Instead, we rely on a recent global study by Vandyck et al. (2018), which uses the transition pathways generated by integrated assessment models, coupled with an air pollution model (TM5-FASST). The study finds that under current air pollution legislation, the UK would experience about 30,000 associated premature deaths per year around 2030 and 40,000 associated premature deaths per year around 2050. Implementing climate change mitigation measures corresponding to a below-2°C policy scenario would reduce this mortality rate by 3,000 per year around 2030 and by 10,000 per year around 2050. By combining air pollution policy mandating best available pollution control technologies with mitigation measures, mortality associated with air quality can be reduced to 14,000 per year in 2050, with air pollution policy and climate policy contributing in similar measures to this significant reduction.

To translate these numbers into a cost to GDP, we quantify each life at £1.83 million (as per Department for Transport, 2016), which corresponds to 0.5–0.6% of 2050 GDP per year. The value of a preventable fatality is likely to be higher in 2050, making this an underestimate.

Dietary change

The typical diet in many countries tends to deviate from the recommendations of healthy eating guidelines, with developed countries consuming, in general, too few portions of fruit and vegetables, too much red meat and too many calories. This leads to increased rates of premature mortality, through increased risk of cancer and cardiovascular disease.

Springmann et al. (2016) carried out a global analysis of both the disease burden and the greenhouse gas emissions of current diets relative to a diet conforming to the WHO's global dietary guidelines. The authors project that global adoption of such dietary guidelines would result in 5.1 million avoided deaths per year in 2050. For the UK, there would be about 60,000 avoided deaths in 2050 (or 980,000 avoided lost years of life), which translates to 2.8% of GDP. Adoption of the global dietary guidelines lies between the 20% reduction in meat consumption that the CCC targets in its core scenario and the 50% reduction that the CCC included as part of its 'further ambition' scenario to reach net-zero in the UK.

Ecosystem co-benefits (and co-costs)

There are many connections between climate policy and ecosystems given the need to sequester carbon through afforestation, improved soil management, reduction in meat consumption and the use of BECCS. As yet, these interactions have not been thoroughly studied and no systematic quantification of the co-benefits and potential trade-offs has been made. Such quantification is a challenging task because the co-benefits and co-costs of mitigation measures in land use are context-specific, which precludes any general conclusions on which measures have the greatest co-benefits and potential trade-offs (Bustamante et al., 2014). However, a few studies give an indication in the context of a temperate climate like that of the UK.

Afforestation projects have been shown to reduce the negative externalities from agriculture, in particular soil erosion and pollution from fertilizers, herbicides and pesticides. Planting and Wu (2003) estimated that such benefits can be equivalent in size to the costs, using the example of an afforestation programme in Wisconsin. A more recent modelling study of an afforestation scheme in river catchments of Scotland suggests that the benefit of afforestation is over twice the cost, thanks to flood regulation, improved water quality and additional opportunities for recreation, as well as carbon sequestration (Dittrich et al., 2019).

A modelling study of US land use suggests that medium-level carbon prices (\$25/tCO_2e) could induce large areas of cropland to be converted to forests or to undergo improved soil management practices. This would in turn create an improvement in water quality throughout the nation, with the greatest increases in the most agriculturally-intensive and water-polluted regions, in particular the nitrogen loadings to the Gulf of Mexico. Afforestation and improved cropland management have therefore demonstrated positive impacts on water quality, soil erosion and flood regulation.

There are also biodiversity co-benefits to climate change mitigation policy but achieving them requires programmes that target both sequestration and biodiversity goals (Bryan et al., 2015). Indeed, the relationship between carbon sequestration and biodiversity in forests is complex and varies by region, depending on the forest's position in the landscape and the design of restoration projects (Wustemann et al., 2017; Pichancourt et al., 2014).

4.3. Macroeconomic opportunities

The integrated assessment models used to estimate climate mitigation costs generally assume a frictionless economy operating optimally. Given this benchmark, climate policy is necessarily costly as it introduces new constraints. However, recent research recognises that the economy is not operating optimally and explores how mitigation policies can improve its efficiency, thereby generating net positive economic effects (Guivarch et al., 2011; Hallegatte et al., 2011; Koberle et al., 2021).

The most significant of the imperfections in the current economic system include:

- Underinvestment in innovation.
- Frictions in the reallocation of workers from one sector to another.
- Underinvestment in skills.
- Underinvestment in capital.
- Losses arising from monopoly power.

Here we draw on a report by the OECD (2017), which places climate policies within the current macroeconomic context of low growth, underinvestment and low interest rates, broadening the policy toolkit to include dedicated fiscal initiatives and structural reforms that can support the low-carbon transition and generate net economic benefits. The OECD's report develops a growth model of an imperfect economy and simulates scenarios where climate policy and pro-growth policies interact. These include an increase in public investment of 0.5% of GDP, increased targeting of R&D spending to clean technologies, more flexible labour markets with broader safety nets, increased investment in skills and active labour market policies and enhanced product market competition to facilitate entry of new players with new technologies.

The OECD finds that, for a net fossil fuel importing advanced economy of the G20, mitigation policies can yield a positive net growth effect in 2050. Direct investments in decarbonisation boost growth by 0.9%, an additional fiscal initiative to increase public investment in skills and education boosts growth by a further 0.6%, and structural reforms and green R&D provide a further boost of 1.3%.

5. Conclusions

The UK is well-positioned to take a leadership role in global decarbonisation efforts, testing the deployment of clean technologies at scale, and demonstrating a path to net-zero, and it has started to do so. The UK is one of the least energy-intensive developed countries due to the low industrial share of its output (18% vs. a global average of 25%). Additionally, due to its low expected future population growth, the UK has a low expected growth in emissions under current policies.

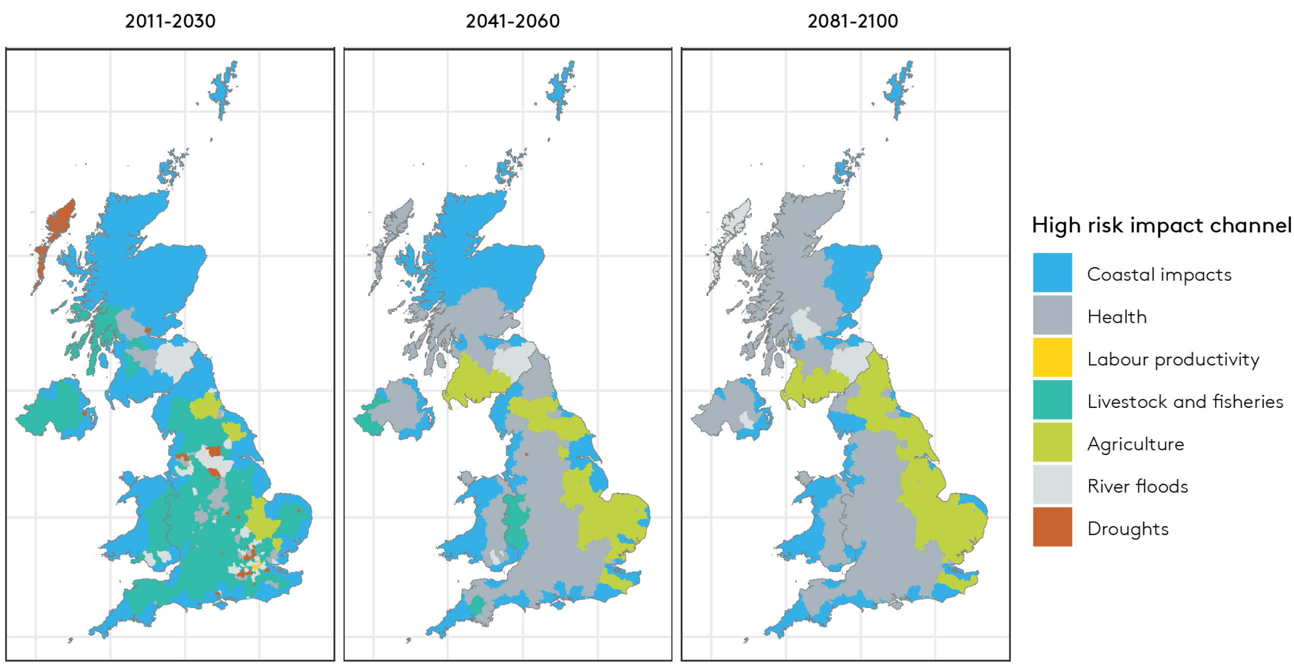
The UK's greenhouse gas emissions have come down from being twice the global average to being in line with it, thanks to a 2% per year decrease in the emissions intensity of economic output, driven mostly by a 64% decrease in emissions from electricity since 1990 and a similar reduction in the waste sector (CCC, 2019). In 2019, the UK legislated that it would become net-zero by 2050, while the Government's Industrial Strategy put clean growth at its heart, recognising the potential for decarbonisation to be a positive contribution to the economy rather than a burden to be minimised (ibid.).

We find that the expected losses to the UK economy from the continued impacts of climate change are considerable, reaching at least 7.4% of UK GDP by the end of the century. The largest risk factor is catastrophic risk: the possibility that the global economy will experience large-scale disruption due to climate change. Losses to agricultural productivity are large in many regions, due to the weakening of the Atlantic Meridional Overturning Circulation (AMOC), which warms Europe (see Annex C). Spillover risks from the rest of the world through trade are also significant.

Proactive investments in adaptation have the potential to reduce these risks. Coastal protection can reduce losses from sea level rise and storm surge by 86%. Expanded irrigation can be used to offset the rainfall changes from changes in the AMOC and preserve much of the UK's agriculture.

Figure 5.1 shows which channels present the greatest expected risk across the UK. Coastal impacts (along most coasts) and livestock and fisheries impacts (in the rural regions) predominate over the period 2011–2030. By 2100, health impacts are the greatest concern in highly populated areas, while agricultural impacts cover the rest of the UK.

Figure 5.1. Channels carrying the greatest expected costs across time periods, under current policies



Transitioning from a current policies scenario to a high mitigation scenario reduces climate change losses by 1.1% of GDP by 2050 and 5.0% of GDP by 2100. At a global level, the benefits of mitigation exceed the costs of mitigation in the latter half of the century, which is a short timeframe for reaping this level of benefits. Combined with the considerable co-benefits of mitigation and the potential for improving economic efficiency, which accrue much earlier, we find strong economic justification for an extensive energy transition to net-zero. The mitigation transition benefits of 4.1% plus the climate risks benefits of moving from a current policies to a high mitigation scenario of 5.0% provide a total benefit to the UK economy of 9.1% of its GDP.

This kind of cost-benefit comparison is difficult to make for the UK as many climate risks are heavily moderated by its cool temperatures. By contrast, climate risks in other countries are expected to be considerably higher – particularly for poor countries within the tropics. Despite recent reductions in fossil fuel emissions, the UK ranks eighth among countries in causing climate change over time (Evans, 2021). These emissions carry costs across the globe that over time are estimated to be equivalent to a loss of £93/tCO_2 (Hänsel et al., 2020) or £39.5 billion per year. This is equivalent to 1.9% of the UK's GDP, more than the expected costs of the transition to net-zero. A net-zero United Kingdom would simultaneously benefit its own economy and economies around the globe.

6. References

AECOM, Delta-EE and University of Exeter (2021) *Cooling in the UK*. London: Department for Business Energy and Industrial Strategy [BEIS]. BEIS Research Paper 2021/050.

Arkell, B. P. and Darch, G. J. C. (2006) Impact of climate change on London's transport network. *Proceedings of The Institution of Civil Engineers-Municipal Engineer*. 159(4), 231-237.

Bednar-Friedl, B., Biesbroek, R. and Schmidt, D. N. (2022) Europe. In *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Cambridge: Cambridge University Press.

Bertram, C. et al. (2021). NGFS climate scenario database: Technical documentation v2.2. Paris: Network for Greening the Financial System [NGFS].

Bressler, R. D. et al. (2021) Estimates of country level temperature-related mortality damage functions. *Scientific reports* 11(1), 1–10.

Bryan, B. A. et al. (2015) Designer policy for carbon and biodiversity co-benefits under global change. *Nature Climate Change* 6(3), 301–305.

Burke, M., Hsiang, S. M., and Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature, 527(7577), 235–239.

Bustamante, M. et al. (2014) Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. *Global Change Biology* 20(10), 3270–3290.

Callaghan, M. et al. (2021) Machine-learning-based evidence and attribution mapping of 100,000 climate impact studies. *Nature Climate Change* 11(11), 966–972.

Carbon Brief (2018) The impacts of climate change at 1.5c, 2c and beyond. Web page. https://interactive.carbonbrief.org/impacts-climate-change-one-point-five-degrees-two-degrees

Carleton, T., Hsiang, S. M. and Burke, M (2016) Conflict in a changing climate. *The European Physical Journal Special Topics* 225(3), 489-511.

CCC [Committee on Climate Change] (2019) Net zero: The UK's contribution to stopping global warming. Technical report.

CCC [Committee on Climate Change] (2021) Progress in adapting to climate change 2021, Progress report to Parliament.

Cheung, M. Y., Liang, S. and Lee, J. (2013) Toxin-producing cyanobacteria in freshwater: A review of the problems, impact on drinking water safety, and efforts for protecting public health. *Journal of Microbiology* 51(1), 1-10.

Ciscar, J. C., Rising, J., Kopp, R. E. and Feyen, L. (2019) Assessing future climate change impacts in the EU and the USA: insights and lessons from two continental-scale projects. *Environmental Research Letters* 14(8), 084010.

Cohen, A. J. et al. (2017) Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015. *The Lancet* 389(10082), 1907–1918.

CRED/UCLouvain [Centre for Research on the Epidemiology of Disasters/Université catholique de Louvain] (2022) EM-DAT International Disasters Database. Brussels: Université catholique de Louvain. www.emdat.be. (Accessed 23 March 2022).

Dasgupta, P. (2021) The economics of biodiversity: the Dasgupta review. London: HM Treasury.

DeFries, R. S. et al. (2019) The missing economic risks in assessments of climate change impacts. *Grantham Research Institute on Climate Change and the Environment*. London: London School of Economics.

Dell, M., Jones, B. F. and Olken, B. A. (2012) Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics* 4(3), 66–95.

Department for Environment, Food and Rural Affairs [Defra] (2022) Agriculture in the United Kingdom 2020. London: National Statistics.

Department for Transport (2016) Transport analysis guidance data book. http://www.gov.uk/government/publications/webtag-tag-data-book-july-2016.

Diaz, D. B. (2016) Estimating global damages from sea level rise with the coastal impact and adaptation model (ciam). *Climatic Change* 137(1), 143–156.

Díaz, S. M. et al. (2019) The global assessment report on biodiversity and ecosystem services: Summary for policy makers. Bonn: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

Dittrich, R., et al. (2019) A cost-benefit analysis of afforestation as a climate change adaptation measure to reduce flood risk. *Journal of Flood Risk Management* 12(4), e12482.

Drupp, M. A., et al. (2018) Discounting disentangled. *American Economic Journal: Economic Policy* 10(4), 109–34.

Environment Agency (2018a) The costs of the winter 2015 to 2016 floods. Bristol: UK Government Environment Agency.

Environment Agency (2018b) A survey of freshwater angling in England. Technical report.

Evans, S. (2021) Analysis: Which countries are historically responsible for climate change? Blog post, 5 October. Carbon Brief. **https://www.carbonbrief.org/analysis-which-countries-are-historically-responsible-for-climate-change**

FAO [Food and Agriculture Organization of the United Nations] (2020) Global forest resources assessment 2020: Main report. Rome: FAO.

Feyen, L., et al. (2020) Climate change impacts and adaptation in Europe: JRC PESETA IV final report. Luxembourg: Publications Office of the European Union.

IPCC [Intergovernmental Panel on Climate Change] (2007) Ecosystems, their properties, goods and services. *IPCC Fourth Assessment Report: Climate Change 2007*. Cambridge: Cambridge University Press.

Gasparrini, A., et al. (2017) Projections of temperature-related excess mortality under climate change scenarios. *The Lancet Planetary Health* 1(9), e360-e367.

Gosling, S. N., et al. (2018) PESETA III: Climate change impacts on labour productivity. Luxembourg: Publications Office of the European Union.

Graff Zivin, J. and Neidell, M. (2014) Temperature and the allocation of time: Implications for climate change. *Journal of Labor Economics* 32(1), 1–26.

Grubenhoff, J. A., du Ford, K., and Roosevelt, G. E. (2007) Heat-related illness. *Clinical Pediatric Emergency Medicine* 8(1), 59-64.

Guivarch, C. et al. (2011) The costs of climate policies in a second-best world with labour market imperfections. *Climate Policy* 11(1), 768–788.

Hänsel, M. C., et al. (2020) Climate economics support for the UN climate targets. *Nature Climate Change* 10(8), 781-789.

Hallegatte, S., et al. (2011) From growth to green growth - a framework. *National Bureau of Economic Research*, Working Paper No. 17841. Cambridge, Massachusetts.

Hallegatte, S., et al. (2016) *Unbreakable: building the resilience of the poor in the face of natural disasters*. Washington DC: World Bank.

Heyes, A., and Saberian, S. (2019) Temperature and decisions: evidence from 207,000 court cases. *American Economic Journal: Applied Economics* 11(2), 238-65.

Howard, P. H. and Sterner, T. (2017) Few and not so far between: a meta-analysis of climate damage estimates. *Environmental and Resource Economics* 68(1), 197–225.

Hsiang, S., et al. (2017) Estimating economic damage from climate change in the United States. *Science* 356(6345), 1362–1369.

Hsiang, S. M. and Jina, A. S. (2014) The causal effect of environmental catastrophe on long-run economic growth: Evidence from 6,700 cyclones, Working Paper 20352. *National Bureau of Economic Research*.

IPCC [Intergovernmental Panel on Climate Change] (2022a) Climate change 2022: Impacts, adaptation, and vulnerability. *Working Group II Contribution to the IPCC Sixth Assessment Report*. Cambridge: Cambridge University Press.

IPCC [Intergovernmental Panel on Climate Change] (2022b) Summary for policymakers. In *Climate Change 2021: The Physical Science Basis*. Cambridge: Cambridge University Press.

Jones, L., et al. (2020) Climate driven threshold effects in the natural environment. Report to the UK Climate Change Committee. UK Climate Risks.

Kahlenborn, W., et al. (2021) Climate impact and risk assessment 2021 for Germany. *Climate Change 27/2021*. Dessau-Roßla: Umweltbundesamt [German Environment Agency].

Kahn, M. E., et al. (2021) Long-term macroeconomic effects of climate change: A cross-country analysis. *Energy Economics* 104, 105624.

Karlsson, M., Alfredsson, E., and Westling, N. (2020) Climate policy co-benefits: a review. *Climate Policy* 20(3), 292–316.

Kjellstrom, T., et al. (2016) Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts. *Annual Review of Public Health* 37:97-112.

Köberle, A. C., et al.(2021) The cost of mitigation revisited. *Nature Climate Change* 11(12), 1035–1045.

Kotz, M., Levermann, A., and Wenz, L. (2022) The effect of rainfall changes on economic production. *Nature* 601(7892), 223–227.

Kotz, M., et al. (2021) Day-to-day temperature variability reduces economic growth. *Nature Climate Change* 11(4), 319–325.

Kulp, S. A. and Strauss, B. H. (2019) New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications* 10(1), 1–12.

Künn, S., Palacios, J., and Pestel, N. (2019) The impact of indoor climate on human cognition: Evidence from chess tournaments, Working Paper 12632. Bonn: Institute of Labor Economics [IZA].

Lobell, D. B., et al. (2008) Prioritizing climate change adaptation needs for food security in 2030. *Science* 319(5863), 607–610.

Missirian, A., and Schlenker, W. (2017) Asylum applications respond to temperature fluctuations. *Science* 358(6370), 1610-1614.

Nardone, A., et al. (2010) Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Science* 130(1-3), 57–69.

Naumann, G., et al. (2020) Global warming and human impacts of heat and cold extremes in the EU. *JRC [Joint Research Centre] PESETA IV Project, Task, 11*. Luxembourg: Publications Office of the European Union.

Nobel, A., et al. (2020) Are biodiversity losses valued differently when they are caused by human activities? A meta-analysis of the non-use valuation literature. *Environmental Research Letters* 15(7):073003.

Nordhaus, W. D. (2013) *The Climate Casino*. New Haven: Yale University Press.

LWEC [Living with Environmental Change Network] (2015) Biodiversity Climate Change Impacts: Report Card 2015. UK Research and Innovation.

OECD (2017) *Investing in Climate, Investing in Growth*. Paris: OECD Publishing.

Office of National Statistics (2022) Climate-related mortality and hospital admissions, England and Wales: 2001 to 2020. UK Census 2021.

POST [Parliamentary Office of Science and Technology] (2019) Climate Change and Agriculture. Research Briefing, POSTnote No. 600. London: UK Parliament.

PESETA III (2018) PESETA III: Climate change impacts on labour productivity. Luxembourg: Publications Office of the European Union.

PESETA IV [Feyen, L. et al.] (2020). Climate change impacts and adaptation in Europe. JRC [Joint Research Centre] PESETA IV final report. Luxembourg: Publications Office of the European Union.

Pichancourt, J.-B., et al.(2014) Growing biodiverse carbon-rich forests. *Global change biology* 20(2), 382–393.

Piontek, F., et al. (2021) Integrated perspective on translating biophysical to economic impacts of climate change. *Nature Climate Change* 11(7), 563–572.

Planting, A. J. and Wu, J. (2003) Co-benefits from carbon sequestration in forests: Evaluating reductions in agricultural externalities from an afforestation policy in Wisconsin. *Land Economics* 79(1), 74–85.

Pretty, J. N., et al. (2003) Environmental costs of freshwater eutrophication in England and Wales. *Environmental Science and Technology* 37(2), 201-208.

Public Health England (2020) Heatwave mortality monitoring report 2020. London: UK Government.

Rao, N. D., et al. (2017) Improving poverty and inequality modelling in climate research. *Nature Climate Change* 7(12), 857–862.

Reid, W. V., et al. (2005) Ecosystems and human well-being-Synthesis: A report of the *Millennium Ecosystem Assessment*. Washington, DC: Island Press.

Riahi, K., et al. (2021) Cost and attainability of meeting stringent climate targets without overshoot. *Nature Climate Change* 11(12), 1063–1069.

Ritchie, P. D., et al. (2020). Shifts in national land use and food production in Great Britain after a climate tipping point. *Nature Food* 1(1), 76–83.

Ritchie, P. D., et al. (2019) Large changes in Great Britain's vegetation and agricultural land-use predicted under unmitigated climate change. *Environmental Research Letters* 14(11), 114012.

Rode, A., et al. (2021) Estimating a social cost of carbon for global energy consumption. *Nature* 598(7880), 308–314.

Rogers, A. A., et al. (2019) Valuing non-market economic impacts from natural hazards. *Natural Hazards* 99(2), 1131–1161.

Rohde, R. A. and Hausfather, Z. (2020) The Berkeley Earth land/ocean temperature record. *Earth System Science Data* 12(4), 3469–3479.

Sayers, P., et al. (2020) Third UK Climate Change Risk Assessment [CCRA3]: Future flood risk. London: Committee on Climate Change.

Sayers, P. et al. (2015) Climate change risk assessment 2017: Projections of future flood risk in the UK. London: Committee on Climate Change.

Semenza, J. C., and Suk, J. E. (2018) Vector-borne diseases and climate change: a European perspective. *FEMS Microbiology Letters* 365(2), fnx244.

Smith, L. A., and Stern, N. (2011) Uncertainty in science and its role in climate policy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369(1956), 4818–4841.

Springmann, M., et al. (2016) Mitigation potential and global health impacts from emissions pricing of food commodities. *Nature Climate Change* 7(1), 69–74.

Statista (2022a) United Kingdom: Distribution of gross domestic product (GDP) across economic sectors from 2010 to 2020. https://www.statista.com/statistics/270372/distribution-of-gdp-across-economic-sectors-in-the-united-kingdom/.

Statista (2022b) Number of deaths in the United Kingdom from 1887 to 2020. https://www.statista.com/statistics/281488/number-of-deaths-in-the-united-kingdom-uk/

Steventon, A., et al. (2018) Emergency hospital admissions in England: which may be avoidable and how? London: The Health Foundation.

Turner, S., et al. (2021) The 2018/2019 drought in the UK: a hydrological appraisal. *Weather* 76(8), 248–253.

Uberoi, E., et al. (2021) UK fisheries statistics. London: UK Parliament.

UK Climate Risk (2021) Flooding and Coastal Change Briefing: Findings from the third UK Climate Change Risk Assessment (CCRA3) Evidence Report 2021.

van Ark, B., and Venables, A. J. (2020) A concerted effort to tackle the UK productivity puzzle. The Productivity Institute Working Paper No. 001. London: UK Economic and Social Research Council.

Van Der Knijff, J., Younis, J., and De Roo, A. (2010) Lisflood: A gis-based distributed model for river basin scale water balance and flood simulation. *International Journal of Geographical Information Science* 24(2), 189–212.

Vandyck, T., et al. (2018) Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nature Communications* 9(1), 4939.

Watkiss, P., Cimato, F., and Hunt, A. (2021) Monetary valuation of risks and opportunities in Climate Change Risk Assessment 3, supplementary Report, prepared for the Climate Change Committee. London: Paul Watkiss Associates.

Weitzman, M. L. (2020) Fat-tailed uncertainty in the economics of catastrophic climate change. *Review of Environmental Economics and Policy* 5(2), 275–292.

Willis, K. G., et al. (2003) *The social and environmental benefits of forests in Great Britain*. Report to Forestry Commission Edinburgh. Newcastle: Centre for Research in Environmental Appraisal and Management, University of Newcastle.

Wüstemann, H., et al. (2017) Synergies and trade-offs between nature conservation and climate policy: Insights from the "natural capital Germany–TEEB DE" study. *Ecosystem Services* 24, 187–199.

Xu, C., et al. (2020) Future of the human climate niche. *Proceedings of the National Academy of Sciences* 117(21), 11350–11355.