Monetary Valuation of Risks and Opportunities in CCRA3

Report to the Climate Change Committee as part of the UK Climate Change Risk Assessment 3

FINAL REPORT

May 2021

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This report was produced by Paul Watkiss Associates. The authors were Paul Watkiss, Federica Cimato, Alistair Hunt.

The work was funded as part of the CCRA3

The work also has received co-funding from the European Union's Horizon 2020 research and innovation programme COACCH project (CO-designing the Assessment of Climate CHange costs) under grant agreement No 776479, as part of deep engagement stakeholder case study work.

COACCH
CO-DESIGNING THE ASSESSMENT OF CLIMATE CHANGE COSTS

The authors wish to acknowledge the comments and feedback on the report from the CCC secretariat, and the Climate Change Committee, as well as from reviewers across Government Departments.

Watkiss, P., Cimato, F., Hunt, A. (2021). Monetary Valuation of Risks and Opportunities in CCRA3. Supplementary Report for UK Climate Change Risk Assessment 3, prepared for the Climate Change Committee, London.

Summary

The UK's Climate Change Risk Assessment (CCRA) aims to analyse the risks and opportunities from climate change to the UK, with the goal of informing the priorities for the UK Government's National Adaptation Programme (NAP) as well as the adaptation programmes of the devolved administrations (DAs). The UK CCRA is undertaken on a five-year rolling cycle and is now on its third cycle (CCRA3).

As part of the specification for CCRA3, the UK Government requested an analysis of the monetary valuation of risks and opportunities, as well as an analysis of the indicative costs and benefits of adaptation. The valuation analysis has been undertaken as a separate exercise and is summarised in this report. This analysis aligns with Step 1 of the urgency method, which establishes the potential magnitude of risks and opportunities. The results of the valuation analysis have been shared with Chapter Authors to provide supporting evidence on the magnitude of CCRA3 risks and opportunities. Alongside this, further work has been undertaken on the costs and benefits of adaptation, which is undertaken for all risks and opportunities that have a higher urgency score. The results of this work have been included in the CCRA3 Technical Report directly, as part of Step 3 of the urgency method, but are also included in this report.

<u>Method</u>

The purpose of this study is to estimate the economic value of risks and opportunities, in monetary terms, as far as possible. This provides one way to help assess the relative importance of different climate change risks to the UK, using a common metric (£) to compare direct impacts within and between sectors. The aim of the analysis is to express the risks and opportunities in terms of the effects on social value (public value), based on the principles and ideas of welfare economics and thus relates to overall social welfare efficiency (HMT, 2020). This focus on social or public value includes all significant costs and benefits that affect the welfare and wellbeing of the population, and therefore includes environmental, cultural, health, social care, justice and security effects. Such an analysis looks at costs and benefits that have direct implications for the economy, but also those that do not involve market prices.

This approach was used in CCRA1 to estimate the order of magnitude of all risks and opportunities in monetary terms (but not an overall aggregate total value, i.e. expressed as a % of GDP). This was possible because CCRA1 was a major new study that undertook new quantitative or qualitative analysis for each individual risk and opportunity. There was no monetary valuation in CCRA2.

For the valuation in CCRA3, indicative estimates of monetary values have been generated for each risk and opportunity as far as possible. These have been estimated for 2°C and 4°C pathways (globally, relative to pre-industrial), both in the mid-century and the end of the century. Where available, estimates are broken down by DA.

However, there are some major differences between CCRA1 and CCRA3. Most importantly, CCRA3 is a synthesis exercise. This has two important consequences. First, valuation is only possible if there is underlying information on physical impacts in the evidence base. Second, physical or monetary estimates are drawn from different studies, which leads to issues of consistency notably:

- Whether the total or marginal effects are reported in the existing evidence. To expand, studies should ideally assess the present-day impact of climate, as well as the total future impact with climate change, as this allows consideration of the additional or marginal impact. However, this is not always the case. In this report, we focus on the total future impact, as this is what the UK needs to adapt to, but where possible we split out the attribution to future climate change.
- Whether the analysis is undertaken for current or future socio-economic conditions. The future impacts of climate change depend on what happens to the future climate, but also what happens to society. Some studies assess the impacts of future climate change on the current population and economy (static). Other studies assess the impacts of future climate on future socio-economic conditions, e.g. on the future population or economy of 2050. Previous studies show

that including future socio-economic change makes a very large difference to the projected impacts and often double impacts (x2) by mid-century. In a synthesis study, it is impossible to standardise socio-economic assumptions. We aim to be transparent and report whether future socio-economic change has been included or not, and if available, to show estimates with and without future socio-economic change.

- Whether current and planned adaptation is included in the existing evidence. In the CCRA3 method, this is assessed in Step 2. In an ideal analysis, the valuation would be undertaken for a counterfactual in Step 1 to establish magnitude, and then reanalysed after taking account of current and planned adaptation (noting this would also provide an estimate of the economic benefit of such adaptation). However, with the exception of a few areas (flooding and water) there is almost no evidence on current and planned adaptation effectiveness. Most of the valuation evidence is therefore presented without existing adaptation, and this may mean the valuation presented could be over-estimating the residual risks of climate change.

It is also noted that the list of risks and opportunities in CCRA3 is more aggregated and generalised than in CCRA1, and in many cases CCRA3 'pools' risks together. For example, CCRA1 included the risk of 'forest extent affected by red needle blight', which could be valued. CCRA3 has 'risks to forestry from pests, pathogens and invasive species' and it is more difficult to try and value such a wide range of outcomes.

Finally, there are a number of differences between this report and the main CCRA3 analysis and evidence chapters that are highlighted. First, risks and opportunities are valued using one of four scores (<£10m/year; £tens of millions/year; £hundreds of millions/year; and >£1billion/year). Second, absolute magnitude values (£) are presented for DAs, whereas in CCRA3, DA magnitude scores are adjusted to reflect similar levels of national equivalence. Finally, for the valuation, scores are presented for central estimates, while CCRA3 considers the upper value of the probability range (i.e. the full UKCP18 10 to 90th range) in its magnitude scoring. Values are presented in current prices, for current and for future periods undiscounted, in order to facilitate direct comparison over time and across scenarios.

<u>Results</u>

The valuation results are presented for each theme below, and for each individual risk and opportunity. The results presented are the estimate of social value at the UK level. DA disaggregation is included (where possible) in the main report. Only one value is presented for 2050, because there is little difference (at the resolution of this study) between the 2 and 4°C pathways at mid-century. For each risk and opportunity, a confidence score is included. In the CCRA3, confidence is based on the quality of the evidence and the level of agreement in the evidence between studies and authors. For the valuation analysis, the confidence score is extended to include confidence in the level of evidence on economic valuation, and also the level of agreement between economic studies. This invariably reduces the confidence down from the main CCRA3 scores.

<u>*Natural Environment*</u>

The focus of the valuation for natural environment in this analysis has been on ecosystem services, i.e. on the provisioning, regulating, cultural and supporting services they provide. However, the natural environment, and the quantification and valuation of ecosystem services, presents a considerable challenge. Indeed, for 5 of the 18 risks, it was not possible to attach any robust valuation scores.

Valuation is easiest (and there is most evidence) for the provisioning services e.g. agriculture, forestry and fisheries, where market prices exist. The analysis of the risks of climate change to these provisioning services indicate potentially high or very high economic costs (£billions/year) to the UK, even by mid-century. However, there are wide differences in the evidence on these risks. Sometimes this is due to the physical impact studies: for example, studies that assess changes in extreme events tend to find more significant negative impacts than studies that only include slow-onset impacts. They also vary according to whether positive aspects are included, notably CO_2 fertilisation.

Interestingly, a further difference is found between studies that focus on physical impacts (and then value changes in production) versus studies that then input these results into economic models. Studies that use partial equilibrium or general equilibrium analysis extend beyond physical metrics (yield) to look at markets, trade and prices, and these generally project much more positive outcomes for the UK, indicating high or very high positive benefits. This is because of the comparative advantage that the UK is projected to gain, as climate change impacts are projected to be larger in many European and international countries. However, while this is positive, these opportunities may not be realised, or limited, due to competing priorities for land and water from other uses and users. There are also unknowns regarding the effects of Brexit on international trade. The wide range of possible outcomes is indicated in the table below, notably for NE6 and NE14/15.

For the regulating services, the effect of climate change on natural carbon stores (NE5) – most notably in soil, trees and seagrass – maybe significant. For example, changes in temperature and precipitation patterns are likely to reduce the ability of soils to retain carbon and so result in carbon emissions. It is possible to quantify these emissions and consider the value of carbon sequestration. Using these approaches, there is the potential for the risk to be Very High. However, there is high uncertainty with the physical pathways and interactions for this risk. It should also be noted that water resources are also a critically important regulatory service but are discussed in relation to infrastructure and health sections that follow.

Quite a large number of CCRA3 risks are focused on pests and diseases (NE2, NE7, NE8, N12, NE16). These are generally assessed as having low or medium impacts, but it is highlighted that this assumes some level of management and control. It was found that these scores could change to high or very high scores if particularly damaging non-invasive species become endemic.

There is a major gap on the valuation of cultural and supporting services, represented by unknown scores in the table above. We suspect that many of these categories would give rise to high or very high valuation scores (i.e. £billions/year), but there is simply not sufficient quantitative risk evidence to assess these in monetary terms. This is a concern because it underestimates the overall economic impacts, and may give the impression that impacts for the natural environment are lower than other themes. We do not believe this is the case.

A number of other insights emerged from the analysis. There is less literature available (than for other themes) on the influence of future socio-economic change on the natural environment, however, it is clear that these changes are extremely important. They include potential changes in land-management, as well as agricultural, forestry and fisheries policy, all of which could have a significant influence on the nature and size of future impacts. This now also includes the very major changes that will need to happen to land-use to deliver the UK's Net Zero commitment (by 2050). For example, the Net Zero commitment may result in a move away from agriculture or livestock areas towards forestry for carbon sequestration. This would affect the various risks and opportunities from climate change on agriculture and forestry. It is also relevant for the potential for risks and opportunities from climate change on natural carbon storage (NE5), i.e. the effects of climate change on sequestration rates or stored carbon (and thus changes in net GHG emissions) associated with forests, peatlands and other natural carbon sinks.

There is also less literature on the influence of current and planned adaptation for the natural environment, and the analysis is complicated by what is assumed about natural acclimatisation, as well as thresholds. It is likely that impacts will rise disproportionately for the natural environment at higher warming, but there is not the evidence to report on exactly when these non-linearities occur. This is shown by higher scores for the 4°C pathway in the table, though this does not fully capture the possible step changes in the scale of impacts that might arise. We therefore caution about reading the results above too positively.

There is also a question of the effects of multiple risks acting together on the natural environment, i.e. this is one area where considering risks individually does not give the full picture. This fact is, therefore, supportive of the use of the natural capital approach to understanding the aggregate effect of climate change risks on the natural environment (Dasgupta, 2021)[i].

Overall, while there is more evidence on the monetary valuation of natural environment risks and opportunities than was available in CCRA1, there remains a major evidence gap for the valuation of the natural environment theme. However, we stress that this is often due to a lack of quantitative information on risks (or opportunities) rather than the valuation step, i.e. the biggest gap is the evidence on what physical impacts will occur from climate change. It is also noted that it was much harder to value the risks and opportunities for this theme in CCRA3 than it was in CCRA1, because CCRA3 groups risks and sub sectors together. Given all of this, we recommend that further work into the quantification and valuation of these risks should be prioritised. Given the location-specificity of many of the risks, this might be advanced through case studies (e.g. for different risk categories and different habitats), which could then be aggregated to provide indicative aggregate estimates

Table ES1. Economic Valuation of Risks and Opportunities for the Natural Environment.

Risk / Opportunity	Present Day	2050s	2080s, 2°C	2080s, 4°C	Confid-ence
NE1. Risks to terrestrial species and habitats from changing climatic conditions and extreme events,	Unknown	Unknown	Unknown	Unknown	Low
NE2. Risks to terrestrial species and habitats from pests, pathogens and invasive species	Unknown	Unknown	Unknown	Unknown	Low
NE3. Opportunities from new species colonisations in terrestrial habitats	Unknown	Unknown	Unknown	Unknown	Low
NE4. Risk to soils from changing climatic conditions, including seasonal aridity and wetness.	H	H	H	H	Low
NE5. Risks to natural carbon stores and sequestration	VH	VH	VH	VH	Low - med
NE6. Risks to and opportunities for:					
Agriculture	L - H (variability)	H / +H	VH / +VH	VH / +VH	Low
Forestry		L - H	L - H	L - H	Low
NE7. Risks to agriculture from pests, pathogens and invasive species	M	M	H	H	Low
NE8. Risks to forestry from pests, pathogens and invasive species	M	M	M	H	Low
NE9. Opportunities for agricultural and forestry productivity from new/alternative species	+M	+H	+H	+VH	Low
N10. Risks to aquifers and agricultural land from sea level rise, saltwater intrusion	L	Unknown	Unknown	Unknown	Low
N11.Risks to freshwater species and habitats from changing climatic conditions and extreme events	H	H	H	H - VH	Low
N12. Risks to freshwater species and habitats from pests, pathogens and invasive species	L	L	L	M	Low
N13. Opportunities to freshwater species and habitats from new species colonisations	+L	+L	+L	+M	Low
NE14. Risks to marine species, habitats and fisheries from changing climatic conditions	L - M	M	M	H	Low
NE15. Opportunities to marine species, habitats and fisheries from changing climatic conditions	+L	+M	+M	+H	Low
NE16. Risks to marine species and habitats from pests, pathogens and invasive species	L	M	M	M	Low
NE17. Risks and opportunities to coastal species and habitats due to coastal flooding, erosion and climate factors	L	M	M	M	Low
NE18. Risks and opportunities from climate change to landscape character	Unknown	Unknown	Unknown	Unknown	Low

Key

Risks		Opportunities		
VH		+VH		£billions/year
H		+H		£hundreds of millions/year
M		+M		£tens of millions/year
L		+L		£<10 million/year

Infrastructure

The valuation results for the infrastructure theme are summarised below. The evidence for this theme is mixed. The most robustly quantified risk is associated with water supply (I8 but reported in H10), which draws on the detailed analysis in the CCRA3 Research reports as well as other studies. A demand/supply deficit is projected to occur in late-century (concentrated in England), with climate change being a key contributor alongside socio-economic change. This will lead to large economic costs, although there is less quantitative economic modelling to date (analysis has focused on physical modelling). Indicative analysis in this study suggests these costs will be high (£hundreds of millions/year), even considering existing adaptation in the water management plans, but further economic analysis is needed.

For approximately half of the infrastructure risks, there are some quantitative estimates, but these are taken from a wide range of studies, which are very inconsistent in terms of methods, climate scenarios, etc. This makes comparison difficult, and further, there is often a range of reported estimates between studies of the same risk (and in some cases, studies even report differences in the sign). It also noted that many of the valuation studies are either highly aggregated (e.g. European scale including the UK) or local (i.e. case studies in a particular location), and there is a gap on robust national level estimates, with the water sector being the exception. For the remaining risks and opportunities, there is not good quantitative information, either because the focus is on hazards that are uncertain (such as changes in the wind regime) or because there is little evidence in the literature. This makes valuation challenging. It is also highlighted that most studies focus on damage to infrastructure assets, and there is less information on how climate change will affect infrastructure services. Both are important to capture overall economic effects.

Based on the analysis undertaken, the most important risks in economic terms - alongside water (I8) - are estimated to be the risks of cascading risks (I1) and flooding to infrastructure directly (I2), both of which are considered to have potential economic costs of £billions/year. The economic costs of indirect/cascading impacts (I1) have been estimated as being between 1.3 to 3 times that of direct impacts of infrastructure failures depending on the approaches and models used, and the range of assumptions in the models. The main challenges is that there is no literature on how cascading risks might change with climate change, i.e. the scale of the increase. The recent WSP CCRA3 research study (2020), however, estimated an increase in overall cascading risk for a 2050 4°C scenario to be 5 – 6 times higher compared to the current baseline. There is good information on the infrastructure assets at risk of flooding (I2), but less robust modelling of the potential annual damages and economic costs, especially as compared to modelling of flooding of buildings. Nonetheless, there is good evidence of the current economic costs of major flood years on infrastructure (including transport and electricity), which are found to be large, especially when indirect costs are taken account of, be this transport disruption (and lost travel time) or electricity outages. There is also quantitative analysis showing that flood hazards are projected to increase with climate change, and thus these costs are projected to rise.

There are a number of other risks to the transport sector. These include risks to bridges (I4), the risk of slope and embankment failure (I5) and risks from high and low temperatures, high winds, lightning (I12). These are all scored individually at the medium level (tens of £million/year), though there are important gaps in the coverage and thus these estimates are partial. It is noted there is less consideration for most non-flood related extremes, and some potentially important gaps on key receptors (bridges, earthworks, embankments).

There are also important risks to the energy sector (beyond flooding). While hydropower is a climate sensitive generation technology (I6), the low levels of hydro-power generation in the UK, and the potential for positive as well as negative effects of climate change, lead to a medium score. Indeed, some studies project potential benefits from changes in the average climate, though there are also projected negative effects from increasing variability. Wind power is also a climate sensitive generation technology (I10), and offshore wind will play a much larger share in electricity generation, as set out in recent Government commitments for 2030). Climate change has the potential to alter future wind regimes. The key problem, however, is that the projected changes in the average wind regime, as well as changes in the intensity, frequency and storms tract patterns for wind extremes, are very uncertain. While there are studies of the economic costs of climate change for the UK, these vary with the projections and scenarios used, and most report a range that includes potentially positive or negative outcomes. What is clear is that given the increasing size (and electricity generated) of the offshore wind industry, even small changes have the potential to have large economic costs or benefits (i.e. high or very high levels). In reality, it is likely that hydro-power and wind-power sectors face a mix of positive and negative effects, with potentially more positive outcomes for changes in the average climate, but more negative outcomes for changes in extremes, though these should not be aggregated because they require different adaptation responses. The risks to other energy generation infrastructure are less clear. While there are potential impacts on thermal generation, with changes in thermal efficiency of current plants (I10) that could be high, or from changes to water availability (I9), the UK electricity mix is changing very rapidly due to the net zero commitment. There is a major evidence gap on how the risks to the energy sector will change as a result of this commitment, both for generation and end-use technology, but there are important potential risks (from both I9 and I10) from a move to gas and/or biomass coupled with carbon capture and storage, as well as an increase in the use of hydrogen generation. These issues are identified as a priority for further consideration, including for adaptation, because a very large new stock of technology will be added over the next 30 years that will be operational in a future climate.

Finally, there is much less information on the risks to the digital sector. Data centres are potentially vulnerable to extreme events such as floods as with other infrastructure, but they also have particularly vulnerability to warmer and peak temperatures, because of the need for mechanical cooling. The costs of cooling for the digital sector will clearly rise with climate change, and some indicative what-if analysis indicates the economic costs of these could be high (noting there are less opportunities for passive cooling, because temperature regulation is critical).

Table ES2. Economic Valuation of Risks and Opportunities for Infrastructure.

Risk / Opportunity	Present Day	2050s		2080s, 2°C		2080s, 4°C		Confid-ence
I1. Risks to infrastructure networks (water, energy, transport, ICT) from cascading failures	H	VH		VH		VH		Low
I2. Risks to infrastructure services from river, surface water and groundwater flooding	H	H – VH		H - VH		VH		Low
I3. Risks to infrastructure services from coastal flooding and erosion	M	M		M		M		Low
I4. Risks to bridges and pipelines from flooding and erosion	M	M		M		M		Low
I5. Risks to transport networks from slope and embankment failure	M	M – H		M - H		H		Low
I6. Risks to hydroelectric generation from low or high river flows	L	M	+M	M	+M	M	+M	Low
I7. Risks to subterranean and surface infrastructure from subsidence	M	M		M		M		Low
I8. Risks to public water supplies from reduced water availability	M	H		H		H		Low-med
I9. Risks to energy generation from reduced water availability	L	Unknown		Unknown		Unknown		Low
I10. Risks to energy from high and low temperatures, high winds, lightning	M	H-VH	+H-VH	H-VH	+H-VH	H-VH	+H-VH	Low
I11. Risks to offshore infrastructure from storms and high waves	L	H-VH	+H-VH	H-VH	+H-VH	H-VH	+H-VH	Low
I12. Risks to transport from high and low temperatures, high winds, lightning	M - H	M – H		M - H		M - H		Low
I13. Risks to digital from high and low temperatures, high winds, lightning	Unknown	M		M		H		Low

Key

Risks		Opportunities		
VH		+VH		£billions/year
H		+H		£hundreds of millions/year
M		+M		£tens of millions/year
L		+L		£<10 million/year

Health, Communities and the Built Environment

The summary of the health, communities and built environment theme are presented below. Note that some risks have been split out, as compared to the CCRA3 Technical report, to allow more disaggregated valuation (including coastal flooding in H2, energy demand for heating versus cooling in H6, air pollution from aeroallergens in H7 and household water supply, noting the latter overlaps with I8).

This theme includes some of the largest economic costs of climate change identified in the overall CCRA3 valuation analysis, but also some of the largest economic benefits (opportunities). This is because it includes risks for which there is high evidence, including several of the most studied risks in both quantitative and monetary terms, and because it has a number of risks that lend themselves to valuation, including for non-market impacts (for health).

There are very large monetary values associated with flooding (river, surface and coastal), extreme heat (on health and well-being) and increased cooling demand. These all individually have estimated costs of £billions/year. There is also a potentially very high magnitude for the impact of climate change on building fabric, though this is driven by storm risk, which is very uncertain.

At the same time, there are also very high benefits (opportunities) from the improvement in health and well-being from warmer temperatures, and from the reduced winter heating demand and energy use, which also potentially run to £billions/year.

It is critical, however, that these risks and opportunities are considered separately and not aggregated in monetary terms, even when they affect the same receptor (i.e. heating and cooling, health benefits and dis-benefits), because they require different adaptation responses.

There are a number of other risks which are assessed as having low or medium monetary values. These include risks from vector-borne disease (H8), air pollution (H7a), and food safety (H9).

There are a number of risks where the evidence is much lower, and where further investigation would be useful, because the risks could be potentially large. This includes aeroallergens (H7b), cultural heritage (H11), health and social care (H12) and H13: Risks to education and prison services.

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There are a number of risks where the evidence is much lower, and where further investigation would be useful, because the risks could be potentially large. This includes aeroallergens (H7b), cultural heritage (H11), health and social care (H12) and H13: Risks to education and prison services.

There is also an important gap on how some of these risks and opportunities will interact with the Net Zero commitment. The most important issue is for the delivery of Net Zero households and the need for low carbon heating (from the combination of fuel substitution and energy efficiency, including insulation). Climate change will affect winter heating demand, and thus the level of heating demand, but it will also increase the risk of summer over-heating, which could be exacerbated in low carbon buildings. Further consideration of the economic costs and benefits of synergistic mitigation and adaptation policy and technology is a priority for this area.

Table ES3. Economic Valuation of Risks and Opportunities for Health, Communities and the Built Environment.

Risk / Opportunity	Present Day	2050s	2080s, 2°C	2080s, 4°C	Confid-ence
H1. Risks to health and wellbeing from high temperatures	VH	VH	VH	VH	Low – medium
H2. Opportunities for health and wellbeing from higher temperatures	+M	+ VH	+ VH	+ VH	Low - medim
H3. Risks to people, communities and buildings from flooding					
H3a River and surface flooding	VH	VH	VH	VH	Medium
H3b Coastal flooding	H	H	H	H	Medium
H4: Risks to the viability of coastal communities from sea level rise	L	L	L	M	Low
H5: Risks to building fabric	Hi	H	VH	VH	Low
H6 Energy demand					
H6a: Opportunities from reduced winter household energy demand	+H	+ VH	+ VH	+ VH	Medium
H6b: Risks from increased summer household energy demand	L-M	H	VH	VH	Low
H7: Risks to health and wellbeing from changes in air quality					
H7a: Risks to health and wellbeing from changes in air pollution	L	L	L	L	Low
H7b: Risks to health and wellbeing from changes in aeroallergens	Unknown	Unknown	Unknown	Unknown	Low
H8: Risks to health from vector-borne disease	L-M	L-M	M	M	Low
H9: Risks to food safety and food security	L	L-M	L-M	L-M	Low
H10: Risks to household water					
H10a: Risks to household water supplies	M	H	H	H	Low-Medium
H10b: Risks to water quality	Unknown	Unknown	Unknown	Unknown	Low
H11: Risks to cultural heritage	Unknown	Unknown	Unknown	Unknown	Low
H12: Risks to health and social care delivery	Unknown	Unknown	Unknown	Unknown	Low
H13: Risks to education and prison services	Unknown	Unknown	Unknown	Unknown	Low

Key

Risks		Opportunities		
VH		+VH		£billions/year
H		+H		£hundreds of millions/year
M		+M		£tens of millions/year
L		+L		£<10 million/year

Business and Industry

The business and industry theme is the one theme where the evidence has changed most significantly since the CCRA1 valuation and there is much more evidence available. This is due in large part to the greater interest in climate-related financial disclosures for physical climate risk, as advanced by the Task Force on Climate-related Financial Disclosures (TCFD, 2017[ii]), the Network for Greening the Financial System (NGFS, 2019[iii]), and the Bank of England. However, there are still relatively few studies of the economic costs of climate change. The analysis indicates that this is an area where there are potentially very large economic costs, but also potentially very large economic benefits.

One of the largest risks (very high, £billions/year) for this theme is from flooding (river and surface) (B1), from the direct and indirect risks involved, the latter including business disruption (captured in B6).

There are also potentially very large risks from climate change to the UK finance, investment and insurance sectors (i.e. to financial services and markets). These involve risks that arise in the UK, but also risks that arise internationally that affect UK businesses and investments (captured in ID8). While it is often difficult to disentangle domestic risks, they are considered to be potentially very high, i.e. equivalent to £billions/year, not least because of issues with rising climate extremes and insurance.

There is also an important risk around labour productivity (B5), though the individual and overall aggregate effects are more uncertain. The UK currently does not have an optimal climate for outdoor work, and there are some important potential benefits for some sectors under future climates. These might be particularly important for Scotland. At the same time, there are potentially large (negative) impacts from heat related effects in the south of England, especially associated with extreme temperatures. These will affect outdoor work, but also indoor productivity, though the latter could occur as either an increase in cooling demand in buildings (given occupational standards) or a decrease in productivity. Either could be very significant in economic terms, especially later in the century (see also H6).

Similarly, there are potentially high risks from disruption to supply chains and distribution, but it is difficult to separate the evidence into the risks that arise in the UK (domestically), and the risks that arise internationally (captured in ID1 and ID7 in the International Chapter). These risks also include elements captured in other risks, e.g. for flooding of sites (B1) and transport disruption (I2).

There are also considered to be large potential benefits (opportunities). Some of these arise from changing conditions in the UK (e.g. the improved suitability for wine growing), some from the comparative advantage gained as other regions internationally suffer potentially greater negative impacts (e.g. Mediterranean summer tourism) and some from the opportunities for new goods or services (in the UK and internationally) that UK businesses could provide (e.g. new insurance products).

Table ES4. Economic Valuation of Risks and Opportunities for Business and Industry.

Risk / Opportunity	Present Day	2050s	2080s, 2°C	2080s, 4°C	Confid-ence
B1. Risks to business from flooding	VH	VH	VH	VH	Medium
B2. Risks to business and infrastructure from coastal change	M	M	M	M	Low
B3. Risks to businesses from water scarcity	M	H	H	H	Low
B4. Risks to finance, investment and insurance	M	VH	VH	VH	Low
B5. Risks to business from reduced employee productivity	L	M	M	H - VH	Low
B6. Risks to business from disruption to supply chains and distribution	M	Unknown but potentially M - H	Unknown but potentially M - H	Unknown but potentially M - H	Low
B7. Opportunities for businesses from changes in demand for goods and services	+M	+VH	+VH	+VH	Low

Key

Risks		Opportunities		
VH		+VH		£billions/year
H		+H		£hundreds of millions/year
M		+M		£tens of millions/year
L		+L		£<10 million/year

International

The final theme, international, is challenging for valuation. This is partly because of the low quantitative evidence base, and high uncertainty around risks and opportunities, but also because the risks may not be ones in which economic metrics are easy to identify (and to value). The confidence for this theme is particularly low, and there are low confidence scores across all risks and opportunities.

There are some potentially large international risks, which could be plausibly £billions/year, notably the risks to food availability (ID1) and risks to the financial sector (ID8). For international food chains, previous food price shocks in the UK have affected a large number of consumers, and thus in aggregate, they can lead to very high economic costs (through rising prices rather than availability of food). For the financial sector, there are potentially large risks, especially because of the UK's central role in the global financial network, though there might also be some potential opportunities for this sector.

There are two risks that are highly contentious in the literature (migration, ID3, and conflict, ID4). The analysis here – while very indicative – indicates that in terms of their economic impact in the UK (only), they may not be high - though we stress there could be very high economic costs in the countries of origin. The other risks generally seem to be low in monetary terms, including public health (ID9, vector borne diseases), and there is one large positive opportunity, from the arctic trade route opening up.

Finally, there are a further set of risks that are much more difficult to quantify and value, which could also be important, but for which there is no evidence. This includes potential risks on international law (ID5), as well as multiplication effects (ID10).

Taken overall, the analysis suggests that while the economic costs of international risks of climate change will rise through the next few decades and be very high in total, the impacts of these overseas on welfare in the UK (domestically) may not be as high as previously reported, at least at mid-century. The exception to this would be under a 4°C scenario, where the limited evidence that does exist suggests a step change in international impacts, and thus potential effects on the UK.

Table ES5. Economic Valuation of Risks and Opportunities for International.

Risk / Opportunity	Present Day	2050s	2080s, 2°C	2080s, 4°C	Confid-ence
ID1: Risks to UK food availability	H	VH / +VH	VH / +VH	VH / +VH	Low
ID2: Opportunities for UK food availability	L	+H	+H	+H	Low
ID3: Human mobility	L	L	L	Unknown	Low
ID4: Violent conflict	L	M	M	H	Low
ID5: Law and governance	Unknown	Unknown	Unknown	Unknown	Low
ID6: Opportunities international trade routes	+L	+M	+H	+VH	Low
ID7: Risks international trade disruption	L	M	H	VH	Low
ID8: Risk finance sector	H	VH	VH	VH	Low
ID9 Public Health	L	L	M	M	Low - Medium
ID10 Multiplication	Unknown	Unknown	Unknown	Unknown	Low

Key

Risks		Opportunities		
VH		+VH		£billions/year
H		+H		£hundreds of millions/year
M		+M		£tens of millions/year
L		+L		£<10 million/year

Discussion

The results above are considered through a number of key questions.

What are the largest risks and opportunities?

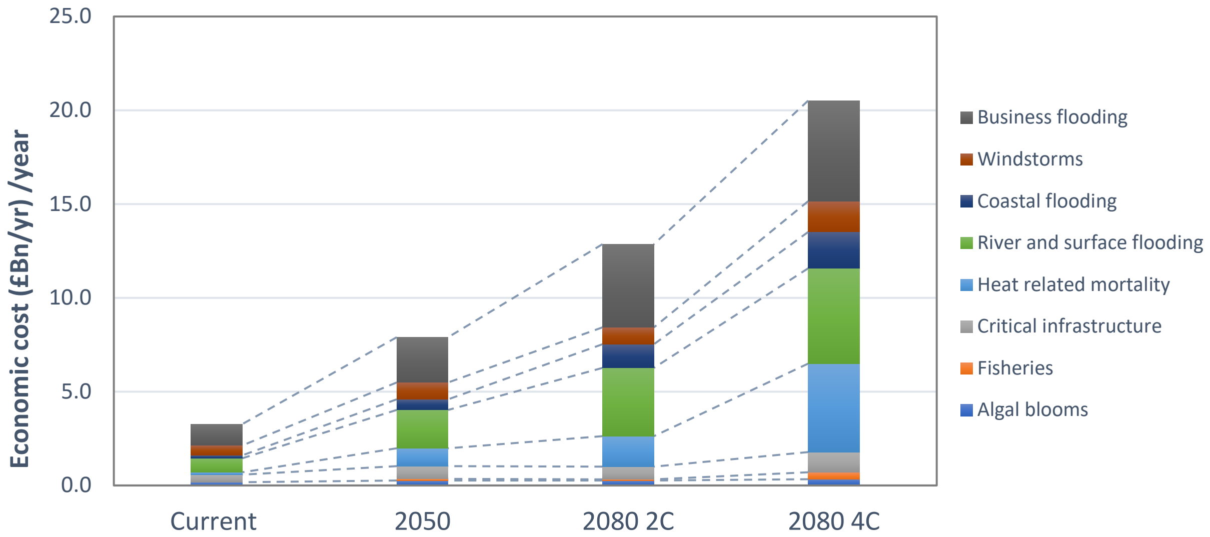
A first finding is that a significant number of known climate threats have very high (aggregate) economic costs (£billions/year) in the UK, even by the mid-century. These include river and surface water flooding to residential properties, business and infrastructure, and the impacts of sea-level rise, coastal flooding and storm-surge to the same receptors. They also include the impact of extreme heat, notably in terms of health and well-being (including fatalities) and overheating in the built environment (residential and business), impacting either in terms of discomfort / reduced productivity, or increasing cooling demand for households and business. The other main hazard, that of water (and the water supply-demand balance) is potentially high in monetary terms in mid- and late-century, although it varies between regions (with England projected to be the most affected). This is projected to occur even though water management plans are already integrating climate change.

There are also large potential costs to business and industry. The evidence in this area has increased since CCRA1, not least because of the interest in climate related financial disclosures. The largest risks are still associated with floods, as well as to financial services, but there is a much wider set of linkages that mean a broader set of risks could be important. Indirect risks (from extremes), cascading risks (to infrastructure) and supply chain risks (business) all potentially involve very high economic costs, though valuation studies are at an early stage. It is highlighted that the focus of this analysis has been on the aggregate values at the national scale. Some risks may not be that large at this scale, but could have high localised costs and have large impacts on particular areas or groups. This cautions against focusing only on the largest risks.

There are almost certainly very large risks to the natural environment, again of the order of £billions/year. These arise from a wide range of risks (including both slow-onset and extreme events), though the evidence base for valuation remains low, both in quantitative and economic terms.

At the same time, there are a number of large economic benefits (also £billions/year) for the UK, again by mid-century, associated with reductions in cold-weather related impacts. These include reduced winter heating demand as well as health and well-being benefits. However, these positives should not be summed against the negatives above, for the same receptors, because they affect different geographical areas as well as different groups, and also require contrasting adaptation strategies. There are also potential benefits (opportunities) for some areas of trade, as the UK may gain a comparative advantage either because the climate becomes more suitable in the UK, or because climate change impacts are greater in competitor countries. These include, for example, tourism and some agricultural products. There are also likely to be some opportunities for the finance sector, and for adaptation services more generally, both with the UK, and for UK businesses overseas. These could help strengthen the case for political engagement in adaptation.

A second key finding is that there is a clear step change in the economic costs of climate change in the UK for a 4°C versus a 2°C future. However, this is often masked in the tables above by the valuation scoring: once a risk is rated as very high (>£1billion/year), the large differences between the two futures (i.e. 2 vs 4°C) are not evident. The underlying valuation (see the chapters) shows large differences in the actual economic costs between the 2 and 4°C worlds, even by mid-century. By the late century the differences are extremely large. This highlights the benefits of global mitigation for the UK. This can be seen in the figure below, which presents the absolute values for a number of key risks. This shows the increase over time, especially in later time periods for a 4°C scenario.



Annual economic costs of climate change in the UK (£Billion) for a selection of risks.

Values include climate and socio-economic change, presented in current prices with no discounting, central values. Note these values are taken from different sources, and thus some care must be taken in the direct comparison, because they use different climate model outputs, scenarios and assumptions.

It is highlighted that there are very large ranges of economic costs (or benefits) for all the risks (and opportunities) above, because of the high uncertainty around future climate change. The valuation scores above present the central estimates, but across the UKCP probabilistic projections, the range of outcomes (and thus values) is very large, and sometimes even changes in sign. This uncertainty is important at the mid-century, at which point in time the climate model uncertainty is usually larger than the difference between a 2 versus 4°C pathway. It is not possible to present the full range of potential economic costs easily and succinctly. It is stressed that for some adaptation decisions, the range of future outcomes, including the upper 90th percentile outcome, will be more important than that of the central value. This also highlights the need to consider uncertainty for any subsequent adaptation assessment. However, while this uncertainty exists, the key message from the valuation analysis is robust, i.e. climate change will have high economic costs in the UK. Further, this uncertainty is not a reason for inaction, and adaptation can be designed to take this uncertainty into account.

What has changed since CCRA1?
One robust conclusion is that the size of the economic costs of climate change in the UK, as assessed by CCRA3, is larger than assessed in CCRA1. A simple comparison between the two valuation assessments is shown below. The number of very high and high risks (but also the high and very high opportunities) is much larger in CCRA3. As an example, there were only three very high risks (>£1Billion/year) identified in CCRA1 but over fifteen in CCR3.

It is difficult to directly compare CCRA1 and CCRA3, because the list of risks and opportunities has changed significantly, but in general, when there is a similar risk description, the CCRA3 score is higher than CCRA1.

These findings – of increasing costs - are mirrored in the international literature, where there has been a general trend of increasing economic costs reported, whether in the global economic models (e.g. the rising social cost of carbon, e.g. Nordhaus, 2017iv) or in regional or national studies (e.g. for the economic costs of climate change in Europe, Szewczyk et al., 2020v). This is happening for a number of reasons.

There have been some changes in the impacts literature that have led to assessments finding higher impacts. In general, there is more consideration of extreme events in physical studies than there was at the time of the CCRA1, and these tend to lead to negative impacts. These tend to shift the overall narrative away from a general trend of winners and losers (from slow-onset change) to primarily a negative impact of climate change in the UK. There is also more information and evidence on the indirect costs of many risks, which increase economic costs, especially for major extreme events.

In terms of hazards, the timing of the CCRA3 means that the new UKCP18 projections have not fed through to many new impact studies. The full consideration of UKCP18 (see the CCRA3 Technical Report) does identify cases where risks have changed, and as new valuation studies emerge, this may increase the monetary valuation estimates further. As an example, the risk of sea-level rise has increased significantly in physical terms since CCRA1 with much higher projections (IPCC, 2019vi), but this is not yet feeding through to higher economic costs as few studies have incorporated the more recent projections at this time.

In addition, more of the studies undertaken since CCRA1 have factored in future socio-economic change. This has a major influence on the size of the results. This can be illustrated with the analysis undertaken for floods: including future population can increase future damages by 20 – 30%, but the inclusion of future economic growth and value-at-risk can double future damages. This also highlights the need to have a more thorough and consistent approach for accounting for these socio-economic effects in future studies.

	2020s	2050s	2080s
Loss of staff hours due to high internal building temperatures	-H	-H - VH?	-H - VH?
Residential properties at significant risk of flooding	-H	-H	-VH
Non-residential properties at significant risk of flooding	-H	-H	-VH
Insufficient summer river flows to meet environmental targets	-H	-H	-H
Climate risks to investment funds	-H?	-H?	-H?
Energy demand for cooling	-M	-H	-H
Summer morbidity due to higher temperatures	-M	-H	-H
Hospitals and schools at significant risk of flooding	-M	-H	-H
Distribution of marine alien/invasive species	-M	-M	-H
Public water supply-demand deficits	+M	-H	-H
Risks to species and habitats due to coastal evolution	-M	-M	-H
Risks to coastal habitats due to flooding	-M	-M	-H
Overheating of buildings	-M	-M	-H
Power stations/sub-stations at significant risk of flooding	-M	-M	-M/H
Increased subsidence risk due to rainfall changes	-M	-M	-M
Agricultural land lost due to coastal erosion	-M	-M	-M
Energy transmission efficiency capacity losses due to heat - over ground	-M	-M	-M
A decrease in output for businesses due to supply chain disruption	-M	-M	-M
Extreme weather event (flooding and storms) mortality	-M	-M	-M
Extreme weather event (flooding and storms) injuries	-M	-M	-M
Heat related damage/disruption to energy infrastructure	-L/M	-L/M	-L/M
Increased ocean acidification	-L	-M	-M
Decline in marine water quality due to sewer overflows	-L	-M	-M
Risks of human illness due to marine pathogens	-L	-M	-M
Forest extent affected by red band needle blight	-L	-L/M	-M
Summer mortality due to higher temperatures	-L	-M	-M
Risk of pests to biodiversity	-L	-M	-M
Risk of diseases to biodiversity	-L	-M	-M
Species unable to track changing 'climate space'	-L	-M	-M
Changes in species migration patterns	-L	-M	-M
Biodiversity risks due to warmer rivers and lakes	-L	-L	-M
Generalist species more able to adapt than specialists	-L	-L	-M
Wildfires due to warmer and drier conditions	-L	-L	-M
Mortality due to summer air pollution (ozone)	-L	-L	-M
Disruption to road traffic due to flooding	-L	-L	-M
Flood risk for Scheduled Ancient Monument sites	-L	-L	-M
Changes in wheat yield (due to warmer conditions)	+H	+H	+H
Reduction in energy demand for heating	+H	+H	+VH
An expansion of tourist destinations in the UK	+H?	+H?	+H?
Decline in winter morbidity due to higher temperatures	+H	+H	+VH
An expansion of tourist destinations in the UK	+H?	+H?	+H?
Decline in winter mortality due to higher temperatures	+M	+M	+H
Changes in sugar beet yield (due to warmer conditions)	+M	+M	+M
Opening of Arctic shipping routes due to ice melt	+L	+M	+M

Risk / Opportunity	2050s		2080s, 2°C		2080s, 4°C	
NE5. Risks to natural carbon stores and sequestration	VH		VH		VH	
I1. Risks to infrastructure networks from cascading failures	VH		VH		VH	
H1. Risks to health and wellbeing from high temperatures	VH		VH		VH	
H3a River and surface flooding	VH		VH		VH	
B1. Risks to business from flooding	VH		VH		VH	
B4. Risks to finance, investment and insurance	VH		VH		VH	
ID8: Risk finance sector	VH		VH		VH	
I2. Risks to infrastructure services from flooding	H – VH		H - VH		VH	
H5: Risks to building fabric	H		VH		VH	
H6b: Risks from increased summer household energy demand	H		VH		VH	
ID7: Risks international trade disruption	M		H		VH	
B5. Risks to business from reduced employee productivity	M		M		H - VH	
I12. Risks to transport (in addition to flooding)	M – H		M - H		M - H	
NE4. Risk to soils.	H		H		H	
NE6. Risks to and opportunities for: *Agriculture*	H	+H	VH	+VH	VH	+VH
ID1: Risks to UK food availability	VH	+VH	VH	+VH	VH	+VH
I10. Risks to energy (in addition to flooding)	H-VH	+H-VH	H-VH	+H-VH	H-VH	+H-VH
I11. Risks to offshore infrastructure from storms and high waves	H-VH	+H-VH	H-VH	+H-VH	H-VH	+H-VH
N11.Risks to freshwater species and habitats	H		H		H - VH	
I8. Risks to public water supplies from reduced water availability	H		H		H	
H3b Coastal flooding	H		H		H	
B3. Risks to businesses from water scarcity	H		H		H	
NE7. Risks to agriculture from pests, pathogens and invasive	M		H		H	
H10a: Risks to household water supplies	H		H		H	
I5. Risks to transport networks from slope / embankment failure	M – H		M - H		H	
NE8. Risks to forestry from pests, pathogens and invasive	M		M		H	
NE14. Risks to marine species, habitats and fisheries	M		M		H	
I13. Risks to digital	M		M		H	
ID4: Violent conflict	M		M		H	
NE16. Risks to marine from pests, pathogens and invasive	M		M		M	
NE17. Risks and opportunities to coastal species and habitats	M		M		M	
I3. Risks to infrastructure services from coastal flooding	M		M		M	
I4. Risks to bridges and pipelines from flooding and erosion	M		M		M	
I6. Risks to hydroelectric generation from low or high river flows	M	+M	M	+M	M	+M
I7. Risks to subterranean and surface infrastructure	M		M		M	
NE6. Risks to and opportunities for: Forestry	L - H		L - H		L - H	
B2. Risks to business and infrastructure from coastal change	M		M		M	
H8: Risks to health from vector-borne disease	L - M		M		M	
ID9 Public Health	L		M		M	
N12. Risks to freshwater from pests, pathogens and invasive	L		L		M	
H4: Risks to viability of coastal communities from sea level rise	L		L		M	
H7a: Risks to health and wellbeing from changes in air pollution	L		L		L	
H9: Risks to food safety and food security	L		L		L	
ID3: Human mobility	L		L		L	
NE1. Risks to terrestrial species and habitats	Unknown		Unknown		Unknown	
NE2. Risks to terrestrial from pests, pathogens and invasive	Unknown		Unknown		Unknown	
NE3. Opportunities from new species colonisations (terrestrial)	Unknown		Unknown		Unknown	
N10. Risks to aquifers and agricultural land from sea level rise	Unknown		Unknown		Unknown	
NE18. Risks and opportunities to landscape character	Unknown		Unknown		Unknown	
I9. Risks to energy generation from reduced water availability	Unknown		Unknown		Unknown	
H7b: Risks to health / wellbeing from changes in aeroallergens	Unknown		Unknown		Unknown	
H10b: Risks to water quality	Unknown		Unknown		Unknown	
H11: Risks to cultural heritage	Unknown		Unknown		Unknown	
H12: Risks to health and social care delivery	Unknown		Unknown		Unknown	
H13: Risks to education and prison services	Unknown		Unknown		Unknown	
ID5: Law and governance	Unknown		Unknown		Unknown	
ID10 Multiplication	Unknown		Unknown		Unknown	
B6. Risks to business from disruption to supply chains / dist	Unknown		Unknown		Unknown	
H2. Opportunities for health and wellbeing from high temp	+ VH		+ VH		+ VH	
B7. Opportunities for businesses from changes in demand	+VH		+VH		+VH	
H6a: Opportunities reduced winter household energy demand	+ VH		+ VH		+ VH	
NE9. Opportunities for agricultural and forestry productivity	+H		+H		+VH	
ID2: Opportunities for UK food availability	+H		+H		+H	
ID6: Opportunities international trade routes	+M		+H		+VH	
NE15. Opportunities to marine species, habitats and fisheries	+M		+M		+H	
N13. Opportunities to freshwater species and habitats	+L		+L		+M	

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Comparison of overall valuation for CCRA1 (left) and CCRA3 (right).

There is, however, one possible exception to the trend of larger impacts in CCRA3 . This is for international risks. CCRA1 only covered domestic risks, and so international risks were omitted. However, at the time of CCRA1, other studies were reporting that the international risks of climate change, i.e. that happened overseas, would cascade back and lead to impacts in the UK that were as large as risks occurring directly (domestically) within the UK (e.g. Foresight, 2011vii). Based on the valuation evidence presented here, this does not seem to be the case for warming of 3°C or below, i.e. domestic risks appear much larger than international risks cascading back to the UK, though this may be due to the lack of evidence, and the difficulty in quantifying these pathways. We also note that this may not be true for business (and certainly some business sectors). We also stress that the economic costs of intentional risks in the countries where these impacts occur (overseas) will be extremely large, and that it is likely that international risks could rise disproportionately for a 4°C pathway later in the century, and at this point, this finding is likely to change.

Finally, an interesting finding from the economic analysis is that when markets are involved, and notably for the provisioning services (agriculture, fisheries and forestry), economic studies using partial or general equilibrium modelling indicate different results to the physical analysis. These economic studies tend to be much more positive for the UK, because they factor in trade and price effects, and project that other countries in Europe and globally experience more negative impacts than the UK (comparatively). However, it is highlighted these studies may not capture all risks due to their aggregated nature, they do not consider other constraints (e.g. over land or water), and they may be over optimistic on market adaptation and the potential for trade (and how this may change with Brexit and other factors).

What is missing?
The evidence base has generally increased since CCRA1 in terms of economic information. However, for 14 of the 61 risks and opportunities, even an indicative score was still not possible. There remains little economic evidence for the natural environment theme, though primarily this is driven by lack of evidence on the physical impacts of climate change, i.e. valuation is not the limiting factor (or at least, not the only limiting factor), and on the dependencies of economic sectors on nature (beyond the provisioning services). Many of the international risks are difficult to approach conceptually, and there is also less economic evidence.

There is also a particular gap identified around Net Zero. These commitments will change the receptors that climate change will act upon (e.g. the energy system), altering risks positively or negatively. At the same time, climate change could make the net zero target harder (or easier) to achieve, e.g. by increasing over-heating risk in summer or reducing energy demand in winter. Further work is needed to consider how the CCRA3 risks could change under a Net Zero future. This is particularly important to encourage synergistic mitigation-adaptation policies.

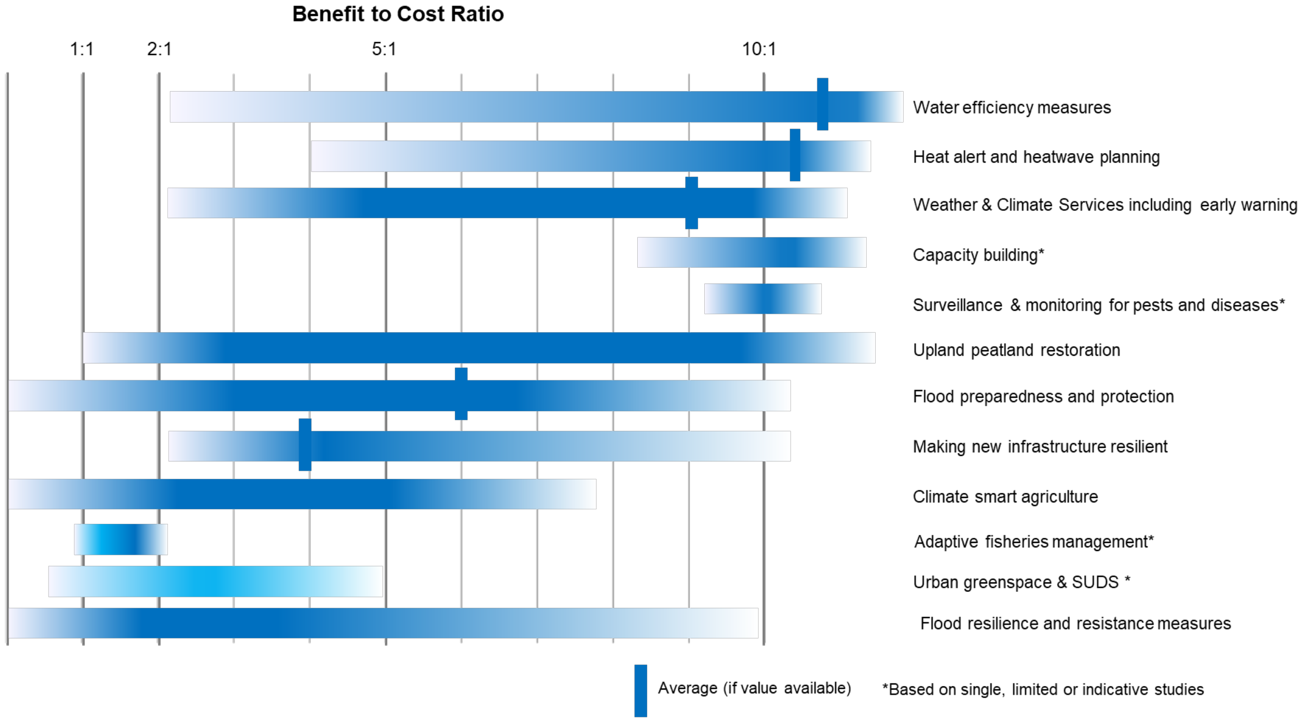
One other area that has been poorly captured in the valuation evidence base is around low probability-high impact events. This includes the so-called climate tipping points, but also high warming scenarios or extreme sea-level rise (including high++ scenarios). There is some limited evidence that indicates that these events could have extremely large economic costs, plausibly even non-marginal, though they would not only affect the UK. These outcomes are critical in the consideration of mitigation policy, because they go beyond the limits of adaptation. Furthermore, a new literature has emerged since CCRA1 on potential socio-economic tipping points (Van Ginkel, 2020viii), which either arise as a cascading impact from a climate tipping point, or arise from a tipping point further down the impact chain. Again, these are a particular concern for high warming scenarios and they could lead to very large economic impacts (e.g. Tesselaar et al, 2020ix).

What are the benefits of further adaptation?
The monetary valuation study in CCRA3 also undertook an evidence review of the costs and benefits of further adaptation action for all individual risks and opportunities, as part of Task 3b of the CCRA3 Methodology. The review findings are reported in the Technical Chapters as a separate section for each risk and opportunity, as well as in this report .

This review was based on the available evidence, thus the findings are partial, and can only be considered indicative. Furthermore, it is stressed that there are a very large number of caveats in transferring the results of existing cost-benefit studies of adaptation. This is due to the high site- and context-specificity, but also because the long time periods and high levels of uncertainty make quantification of benefits and thus economic analysis challenging.

Nonetheless, the review found an increased body of evidence, particularly since previous CCRAs, and identified potentially high economic benefits from further adaptation for many of the CCRA3 risks and opportunities. The findings for a selection of individual risks are summarised in the figure below.

This identifies that many early adaptation investments deliver high value for money. The benefit-cost ratios typically range from 2:1 to 10:1 – i.e., every £1 invested in adaptation could result in £2 to £10 in net economic benefits. The analysis also found that adaptation also often leads to important co-benefits, so as well as reducing potential losses from climate change, it often generates direct economic gains, or leads to social or environmental benefits. There are benefits from taking further adaptation action for almost every risk assessed in the CCRA report.



Benefit to Cost ratios for Adaptation for Selected CCRA3 risks.

Notes: Figure shows the indicative benefit:cost ratios and ranges for a number of adaptation measures. It is based on the evidence review undertaken in the CCRA3 Valuation study, which was co-funded by the EU's Horizon 2020 RTD COACCH project (CO-designing the Assessment of Climate CHange costs). Vertical bars show where an average BCR is available, either from multiple studies or reviews. It is stressed that BCRs of adaptation measures are highly site- and context-specific and there is future uncertainty about the scale of climate change: actual BCRs will depend on these factors.

This highlights that there are benefits to acting early. Furthermore, delaying adaptation will make it much harder to tackle future climate risks and may make large future costs inevitable: opportunities for building resilience will decline with time (GCA, 2019[x]).

At the same time, some decisions and actions can be delayed: a key issue is therefore to identify where what is urgent to do now, and what can be done later as part of an iterative, adaptive management approach. There are three areas where early action is needed and can be justified in economic terms (Watkiss and Betts, 2021[xi]).

First, as highlighted above, the UK already experiences large economic costs from climate extremes today, and these are growing. There are therefore large net economic benefits today from reducing these with low- and no-regret actions, which have high benefit to cost ratios (OECD, 2015[xii]).

Second, in some areas there is a large economic cost from delaying action. This involves decisions or investment that could lead to very large future economic costs, that will be costly to address or are irreversible. There is a one-off opportunity to avoid these risks now, but if this is not taken, we commit (lock-in) to large future impacts. A good example is infrastructure. Infrastructure built over the next five years will operate under a very different climate to today. If these future risks are not considered, climate change will cause asset damage or failure, and affect operating costs and/or revenues. There is a one-off opportunity to design infrastructure to be climate resilient when it is built, and this has a benefit to cost ratio of 4:1 (Hallegette et al., 2019[xiii]). A further example is with the hundreds of thousands of new homes being built each year in the UK, which are currently not designed for future overheating risks. Similar issues arise with land-use, as this locks-in development patterns for decades.

Finally, there are some extremely low-cost preparatory actions that can be taken to improve future decisions, effectively providing option values[xiv]. This involves developing adaptive management plans, especially for decisions that have long lead times or involve major future change in the future that is uncertain.

What has been difficult and what are recommendations for future analysis?
The valuation exercise in CCRA3 has been much more challenging than in CCRA1, because of the use of a synthesis approach in the underlying CCRA Technical Report. It has required more work to go back to the primary physical impact literature, and it has relied more on the use of existing economic studies in a synthesis analysis. In turn, this has made the reporting and direct comparison of monetary values for individual risks and opportunities problematic, because primary studies use different scenarios, socio-economic assumptions, etc. This means the valuation results here are 'messier' than for CCRA1.

Looking forward, it is notable that by the time of CCRA4, it will have been fifteen years since a systematic, comprehensive and consistent analysis of risks and opportunities for the UK has been conducted, including an economic assessment. Given the scale of economic cost being projected in CCRA3, and the need to inform future risk management and adaptation decisions, it is important to plan how CCRA4 can incorporate a more advanced analysis (including economic analysis).

Finally, alongside any analysis of risks and opportunities, there is a need to improve the economic analysis of how current (and planned) adaptation is reducing these future risks (or enhancing opportunities). There is very little information – from either government policy studies or the academic literature – on the real-world impact of current adaptation. This is partly because there is insufficient ex post data, and partly because ex ante studies are very difficult. However, it is a major gap and would have significant benefits for the economic analysis in CCRA4.

Table of Contents

Introduction

The Third UK Climate Change Risk Assessment (CCRA)

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

The UK CCRA is undertaken on a five-year rolling cycle and is now on its third cycle (CCRA3). Work is currently underway to produce the third CCRA Evidence Report, due for publication in 2021. The objective of the Evidence Report is to review and analyse the evidence on priority risks and opportunities for England, Northern Ireland, Scotland and Wales and by doing so, to help provide information of relevance for the next round of Government-led adaptation programmes. This Evidence Report will therefore inform the CCRA3 Government Report (due for publication in 2022) and the third NAP and the third adaptation programmes of the devolved administrations (DAs), due to be published from 2023. The information in the CCRA3 Evidence Report is, however, also likely to be of interest to a wider audience.

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

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

These adaptation programmes may include direct public sector action (by government, agencies, regulators, etc.), but also interventions that create the enabling environment for others to adapt, i.e. for utilities, the private sector and households.

To provide this information, the CCRA focuses on the urgency of risks and opportunities. Urgency is defined as a measure of the level of action that is needed in the next five years to reduce a risk or realise an opportunity from climate change, noting that these near-term actions may address risks or opportunities in the short, medium or long-term. To ensure that the information provided is relevant for the respective adaptation programmes, the assessment is undertaken for each individual country (England, Northern Ireland, Scotland, Wales), rather than for the UK.

As with CCRA2, the **CCRA3 Evidence Report is based on a synthesis exercise**, rather than a new national quantified assessment. It draws on the large body of peer-reviewed scientific literature and grey literature on climate change, risks and adaptation in the UK, complemented with new CCC commissioned research in key areas. It uses this evidence alongside expert judgement in assessing risks and opportunities, building on expertise in the international context as well as previous CCRAs.

For risks and opportunities, the method uses an **urgency scoring framework**. This is shown below and uses three questions to elicit the urgency score. Risks and opportunities are given one of four possible scores, reflect more or less urgency.

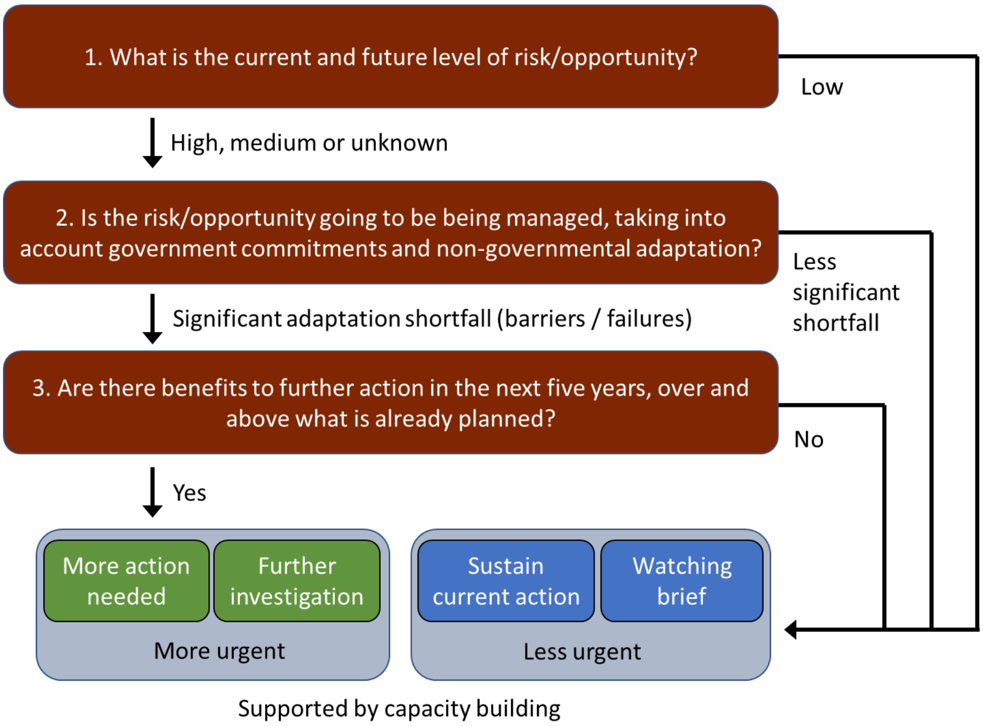


Figure 1. Urgency Scoring Framework. Updated from CCRA2.

Monetary Valuation of Risks and Opportunities

As part of the development of CCRA3, the UK Government (Defra) produced a 'Customer Requirement Document for CCRA3' for the Committee on Climate Change. This included some guidance on the approach and key outputs. There was also a subsequent request from Defra, as part of discussions on the Customer Requirement, to **assess risks and opportunities in monetary terms, and to consider the indicative costs and benefits of adaptation**. This recognised that although CCRA1 had undertaken monetary valuation, CCRA2 (due to lower resources) had not.

The valuation analysis has been undertaken as a separate exercise and is summarised in this report. The valuation of risks and opportunities aligns with Step 1 of the urgency method, which established the potential magnitude of risks and opportunities. The results of the valuation analysis have been used (with Chapter Authors) to provide supporting evidence on the magnitude of CCRA3 risks and opportunities.

The work on the costs and benefits of adaptation, which is undertaken for all risks and opportunities that have a higher urgency score, has been included in the CCRA3 evidence report directly, as part of Step 3 of the urgency method. They are also reported in this report, as an additional section to each risk or opportunity.

This report presents the monetary valuation only. The first section provides an initial section to frame the analysis, to highlight the overall objective and set out what is and what is not included. The second section presents the methodology. The third section presents the valuation results, for each CCRA3 chapter and each individual risk and opportunity. Finally, key conclusions and recommendations are presented.

Methods and Framing

Objectives and Framing for Valuation

The purpose of this study is to monetise risks and opportunities as far as possible. This provides one way to help assess the relative importance of different climate change risks in the UK, using a common metric (£) to compare direct impacts within and between sectors. The aim of the analysis is to express the risk in terms of the effects on social welfare, as measured by individuals' preferences using a monetary metric. This values market and non-market impacts, and includes consideration of environmental, economic and social costs, not just financial impacts.

Monetary Valuation in CCRA1 and CCRA2

The monetary valuation of climate risks was included in the First UK Climate Change Risk Assessment (CCRA1) (Watkiss and Hunt, 2011). The approach for valuation was based on economic appraisal guidance from HM Treasury Green Book and Government Departments for economic appraisal.

An attempt was made to value each individual risk or opportunity in CCRA1. However, the feasibility of valuation depended on the level of quantification from the previous step in the CCRA1 process. In some cases where there was quantitative risk information, valuation was undertaken. In cases where there was only qualitative information, an indicative analysis was undertaken and an order of magnitude of potential valuation was made, based on available evidence and expert judgement.

As CCRA1 involved new quantitative and qualitative analysis for each risk and opportunity, the overall analysis was undertaken consistently for each time periods (current, 2020s, 2050s, 2080s) and for the low, medium and high UKCP09 scenarios. Where possible, socio-economic and climate risks were reported separately and together, i.e. economic costs with climate change hazards and population increases, and for the changes from the climate hazard alone.

The synthesis output from CCRA1 is shown in box 1[1].

Within CCRA1, it was <u>not</u> possible to estimate an aggregate total monetary value for climate change in the UK, nor to generate an equivalent % of GDP value (i.e. a Stern review type number). This was because there was no quantitative information on all risks, and providing estimates only for a sub set of risks would be misleading, as it would underestimate the economic cost of climate change.

The valuation of risks and opportunities was not undertaken in CCRA2.

[1] There are important caveats with these results, as reported in CCRA1. Some results are presented for a scenario of future climate change only, whilst others include climate change under assumptions of future socio-economic change. It is also stressed that in some cases the magnitude of the impact (or opportunity) changes across the full UKCP09 projections (the p10 to p90 range) and in some cases even changes in sign. It is noted that some care must be taken in aggregating risk categories, as there are some overlapping impacts, and thus the risk of double counting at the UK level. Further, it is stressed that these results do not include autonomous adaptation, and in general, do not take account of existing planned adaptation measures. It is stressed that the list of possible impacts is partial, Further, consideration of the range of scenarios – and the range of estimated levels of future climate change – include much higher economic costs associated with higher rates of changes, non-linear increases, and exceedences of threshold levels. Finally, these current estimates do not include consideration of the economic costs of climate change overseas, and how these might affect the UK, or the potential economic costs of major events post 2100. All of these issues are critical to the assessment of the overall aggregate costs of climate change in the UK.

Box 1. CCRA1 Summary. Range of potential magnitude in the 2050s (all estimates) and time of onset (medium emissions, central estimate) for risks important from an economic perspective

	2020s	2050s	2080s	Confidence
Financial impact of industry assets at risk of flooding	-H	-H	-VH	High
Residential properties at risk of flooding	-H	-H	-VH	
Non-residential properties at risk of flooding	-H	-H	-VH	
Crop yield (wheat)	+H	+H	+H	Medium confidence
Decrease in demand for heating	+H	+H	+VH	
Redcution in winter morbidity	+H	+H	+VH	
Crop yield (sugar beet)	+M	+M	+M	
Water supply demand deficits	+M	-H	-H	
Ocean acidification	-L	-M	-M	
Coastal evolution due to sea-level rise	-M	-M	-H	
Ecological impacts due to inundation from coastal flooding	-M	-M	-H	
Buildings affected by subsidence due to rainfall changes	-M	-M	-M	
Agricultural land lost due to coastal erosion	-M	-M	-M	
Flood risk for agricultural land	-M	-H	-H	
Summer morbidity	-M	-H	-H	
Extreme weather event (flooding and storms) injuries	-M	-M	-M	
An expansion of tourist destinations in the UK	+H?	+H?	+H?	Low confidence
Reduction in winter mortality	+M	+M	+H	
Arctic sea ice extent - number of navigable days	+L	+M	+M	
Warmer rivers and lakes	-L?	-L?	-M?	
Generalist species benefiting at the expense of specialists	-L?	-L?	-M?	
Wildfires due to warmer and drier conditions	-L?	-L?	-M?	
Impact of pests on biodiversity	-L?	-M?	-M?	
Impact of disease on biodiversity	-L?	-M?	-M?	
Species unable to track changing climate space	-L?	-M?	-M?	
Changes in species migration patterns	-L?	-M?	-M?	
Heat related damage/disruption to energy infrastructure	-L/M	-L/M	-L/M	
Flood risk for Scheduled Ancient Monument sites	-L	-L	-M	
Forest extent affected by red band needle blight	-L	-L/M	-M	
Summer mortality	-L	-M	-M	
Health impact of summer air pollution (ozone)	-L	-L	-M	
Changes to marine water quality	-L	-M	-M	
Incidents of shellfish related human illness	-L	-M	-M	
Flood disruption/delay to road traffic	-L	-L	-M	
Energy demand for cooling vehicles	-L	-M	-M	
Agricultural areas at risk from flooding	-M	-M	-H	
Changes in soil organic carbon	-M?	-M?	-H?	
Overheating of buildings	-M	-M	-H	
A decrease in output for businesses due to supply chain disruption	-M?	-M?	-M?	
Energy transmission efficiency capacity losses due to heat - over ground	-M	-M	-M	
Flooding of energy infrastructure	-M	-M	-M	
Demand for cooling	-M	-H	-H	
Flooding of energy infrastructure	-M	-M	-M/H	
Hospitals at risk of flooding	-M	-H	-H	
Extreme weather event (flooding and storms) mortality	-M	-M	-M	
Distribution of marine alien/invasive species	-M	-M	-H	
Population affected by water supply deficits	-M	-M	-M	
Impact of climate on funds and fund management	-H?	-H?	-H?	
Loss of staff hours due to high internal building temperatures	-H?	-H - VH?	-H - VH?	
Rivers meeting WFD flow targets	-H	-H	-H	
Payout costs by the insurance industry due to flooding	-VH	-VH	-VH	
Urban Heat Island effect	-L/M	-M/H	-M/H	
Effectiveness of green space for cooling	-L	-L	-M	

Key: Red = impact. Green = benefit
Low, <£0 m, Medium, £10 million to £100 million, High, £100 million to £ billion, Very high, >£1bililon.

Valuation of risks and opportunities in CCRA3

The approach for meeting the customer requirement, and undertaking valuation in CCRA3, follows the same methodological approach as undertaken in CCRA1. The aim of this exercise is to estimate the potential monetary values of all risks and opportunities in terms of the effects on social welfare. However, there are some major differences between CCRA1 and CCRA3, which mean a different approach is required.

- CCRA3 is a synthesis exercise, which limits what is possible. It also makes it difficult to deliver a consistent set of valuation estimates.
  - In CCRA1, a new analysis was undertaken for each risk and opportunity using consistent methods and consistent (harmonised) socio-economic and climate scenarios.
  - In CCRA3, there is no new analysis (other than from the research projects), and thus valuation is only possible if there is existing evidence, e.g. if there are quantitative or semi-quantitative estimates in the literature. There is therefore likely to be a much greater use of expert judgement in CCRA3.
  - In CCRA3, the use of existing evidence from different studies (for each risk) means that there will be much less consistency between risks, especially in terms of climate scenarios and socio-economic scenarios.

- CCRA3 has more aggregated risks than CCRA1.
  - In CCRA1, risks were described with much greater granularity, and focused on a specific physical endpoint. This makes it easier to apply government economic appraisal, with the use of monetary unit values.
  - In CCRA3, risks and opportunities are often pooled together. This reduced down the number of risks/opportunities, but makes quantitative analysis more challenging. As an example, CCRA1 had the defined risk of 'forest extent affected by red needle blight' while CCRA3 has the more generic category of 'risks to terrestrial species and habitats from pests and pathogens'. It is much easier to provide a valuation endpoint for a specific risk (e.g. red needle blight in CCRA1) than for a very broad category of all pests and pathogens (in CCRA3). Further, the broad categories in CCRA3 involve much more work (as they involve all risks, not just one single risk). To address this, the proposed approach in CCRA3 is to use examples and case studies to explore the importance of risks when broad categories are involved.

- The resources available for valuation are low.
  - The available resources for the CCRA3 valuation exercise are very modest. The allocated time per risk / opportunity is extremely low, given there are other 60 risks and opportunities to consider. This has limited what is possible and CCRA3 valuation relies more on synthesis than new analysis.

CCRA3 monetary valuation analysis

While valuation (monetisation) is sometimes considered controversial, it is a standard part of government economic appraisal, as set out in the HM Treasury Green Book (HMT, 2020[xv]). This is based on the principles of welfare economics – that is, how the government can improve social welfare or wellbeing. The Green Book outlines that the costs or benefits of policies or projects – relative to a baseline and towards a goal - should be valued and monetised where possible in order to provide a common metric.

The aim of CCRA3 is therefore to monetise all risks and opportunities as far as possible, expressing these in terms of the effects on social welfare or wellbeing, i.e. for society overall. It is recognised, however, that it is much more challenging to value some of these risks and opportunities, especially those in non-market sectors. This includes in particular the natural environment theme. It is therefore very important to acknowledge if valuation gaps exist, and report these alongside any estimates, otherwise there can be an underestimation of the overall economic cost of climate change.

In CCRA1, values were presented as annual economic values, related to information on annual risks or opportunities. This included annual impacts (as arising from slow onset climate change impacts) as well as probabilistic events (extremes), with the latter being reported as annualised average damage / equivalent annual damage. Central estimates were reported. However, this underestimates the importance of large-scale events, both in terms of their direct costs, and also the wider indirect cost (wider economy effects) that large events can cause. Therefore, in CCRA3 valuation, there is some consideration given in valuation to 'events' as well as annualised damages.

In CCRA3, in Step 1, an analysis of the magnitude for risks and opportunities is made. A long list of metrics is provided, which includes the potential for using monetary values. This is shown in Table 1 below. Alongside this, CCRA3 assesses the confidence, based on the quality of the evidence and the level of agreement in the evidence between studies and authors.

Table 1. CCRA3 Magnitude table – showing valuation metrics only.

	High Magnitude	**Medium Magnitude**	**Low Magnitude**
Quantitative evidence	*Major annual damage and disruption or foregone opportunities:*[1]	*Moderate annual damage and disruption or foregone opportunities:*	*Minor annual damage and disruption or foregone opportunities:*
	-£hundreds of millions damage (economic) or foregone opportunities, and/or	-£tens of millions damage (economic) or foregone opportunities, and/or	-Less than £10 million damage (economic) or foregone opportunities, and/or
	-Other metrics (physical, social, environmental), see method chapter.	-Other metrics (physical, social, environmental), see method chapter.	-Other metrics (physical, social, environmental), see method chapter.

In CCRA3 the risks and opportunities are scored separately for each of the four countries (England, Scotland, Wales and Northern Ireland. In CCRA3, an adjustment factor is included, as CCRA3 focuses on the relative importance for each DA. Note that in the valuation analysis in this report, we focus on the absolute valuation estimates, i.e. the adjustments in Table 2 are **not** used.

Table 2 Adjustment factors for scoring magnitude for devolved administrations. Note these are not used in the monetary valuation report.

	UK / England	**Wales**	**Scotland**	**Northern Ireland**
Economics	As table above	Metrics in table above adjusted for gross value added[1], thus to give relative importance, values in table are reduced by 1 order of magnitude, and applied equally to Northern Ireland/Scotland/Wales. • £tens of millions damage or foregone opportunities, • £ millions damage or foregone opportunities • Less than £1 million damage or foregone opportunities.		

For the valuation in CCRA3, the aim is to try and focus on the monetary valuation for the magnitude score. The results are presented in terms of the indicative values. However, an additional category has been included, which represents costs or benefits> £1billion/year. The table is presented below.

Table 3 Magnitude categories proposed for CCRA3 valuation (annual values).

Very High Magnitude	High Magnitude	Medium Magnitude	Low Magnitude
>£1billion damage (economic) or foregone opportunities	-£hundreds of millions damage (economic) or foregone opportunities	-£tens of millions damage (economic) or foregone opportunities	-Less than £10 million damage (economic) or foregone opportunities

In CCRA3, the scoring the magnitude of risks and opportunities is included for 2°C and 4°C pathways, both in the mid-century and the end of the century, relative to pre-industrial. However, because CCRA3 is a synthesis exercise, it is rarely the case that underlying studies provide the exact evidence for these futures. The scenarios and some of the evidence used is summarise below.

- 2ºC world. A scenario that limits global mean temperature to 2ºC relative to pre-industrial, i.e. consistent with the Paris Agreement. This assumes temperatures are 2ºC (or below) by the end of the century and that there are no overshoots. However, as these goals are set using emission reduction targets, there is uncertainty around the exact level of temperature change that will be experienced. In terms of synthesis material, this often draws on the earlier UKCO09 low scenario, or the IPCC Representative Concentration Pathways (RCP) 2.6.
- 4ºC world. A counter-factual scenario with little mitigation, leading to global mean temperatures of 4ºC relative to pre-industrial by the end of the century (approximately). However, this needs to take account of the range of (equilibrium) climate sensitivity in the climate models, and even if there is an emissions pathway that might lead to a median chance of 4ºC of warming, the range experienced could be from 3 to 5ºC. This draws on the UKCO09 high scenario, or the IPCC Representative Concentration Pathways (RCP) 6.0 or 8.5.

These pathways are considered for the following time periods:

- Current (recent historic);
- Mid-century (2050s, i.e. 2041-2060);
- Late-century (2080s, 2080 – 2099).

This is shown below.

Table 4 Magnitude scoring in CCRA3.

Magnitude scores					
Country	Present Day	2050s, on a to pathway stabilising at 2°C by 2100*	2050s, on a pathway to 4°C at the end of the century#	2080s, on a to pathway stabilising at 2°C by 2100*	2080s, for 4°C world at the end of the century#
England					
Northern Ireland					
Scotland					
Wales					

*This scenario is aligned broadly to the Paris Agreement and the goal of limiting global mean temperature to well below 2°C above pre-industrial levels.

This scenario is defined around outcomes that lead to approximately 4°C global mean temperature above pre-industrial levels by the end of the century. This is strictly defined as the period 2080 to 2100. However, because CCRA3 is a synthesis exercise, a pragmatic approach is adopted that considers a range of modelling scenarios that fall slightly outside this range. Details on what is included are provided in the separate guidance section.

Note that in CCRA3, the score is based on the highest value in each cell, as captured by the 10th to 90th percentile of the UKCP projections. For the CCRA3 valuation, we have focused more on central values.

Alongside this, the analysis reviews where there is evidence of Low likelihood, high impact scenarios. These involve a set of possible outcomes that lie outside the core scenarios above. They include tail-end risks, High++ scenarios, as well as earth system instabilities (tipping points). These are important, because they could have extremely large economic costs and represent outcomes that we would definitely wish to avoid.

Socio-economics and current adaptation

In a synthesis exercise, as for CCRA3, it is very difficult to provide consistent and harmonised estimates of monetary values. This is because the study must draw on existing evidence (rather than generating new harmonised numbers). This means there is much less consistency between modelling methods, climate projections used, socio-economic data and scenarios used, time periods considered, etc.

In practice, this becomes extremely complicated very quickly because there is a huge variation in how results are presented. This hampers direct comparability. The following effects are highlighted.

Total versus marginal. Some of the evidence (which CCRA3 will draw on) generates estimates of the total impacts of climate change, i.e. current plus the future change, will some evidence is for the marginal impacts of climate change (alone).

In this report, we provide values for the total, because adaptation needs to be undertaken in response to the aggregate sum of future impacts (climate and socio-economic) irrespective of the attribution. However, it can influence the type of adaptation, i.e. whether planned activities address socio-economic drivers and/or climate drivers of change.

Current socio-economics or future socio-economics. The future impacts of climate change depend on what happens to the climate, but also the future society that climate acts upon. In the future, there will be changes in the stock of risk and thus exposure to climate hazards, as well as the vulnerability and adaptive capacity. To put it simply, a flood in a future year is likely to have a greater impact than today, just because there will be more people, or a greater value at risk. The assumptions about future socio-economic change make a large difference to results, and involve complex interactions, discus

There is little consistency on these issues in the literature. Some studies consider the future risks of climate change on the current socio-economic conditions and the current economy (static socio-economics). Other studies include the combined impacts of future climate and future socio-economic change together[2], or include some socio-economics for some elements (e.g. population growth) but not others (e.g. including population but excluding economic growth).

These considerations are not trivial. Previous studies (e.g. Rojas et al., 2013[xvi]: Brown et al., 2011[xvii]) typically find that socio-economic change such as population increase or economic growth is at least as important as climate change in determining the overall magnitude impacts in future periods. While the influence of socio-economics is often dominant at mid-century, it is still very large in the late century, as shown by studies that compare Shared Socio-economic Pathways (SSPs) (e.g. see Hinkel et a., 2014[xviii]).
s in the box below.

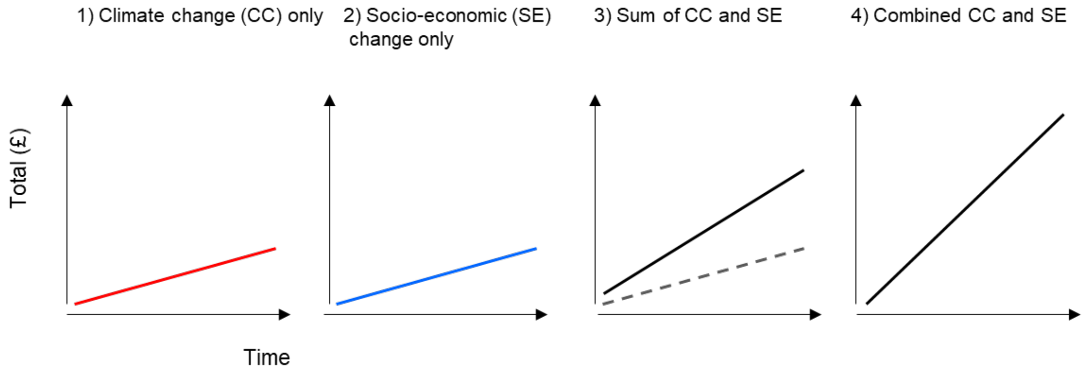
[2] The combined effects of socio-economic and climate change together provides the total risks faced, but care should be taken when attributing the relative (or marginal) risk due to climate change specifically, since this is measured here as being incremental to the current socio-economic baseline.

Box 1 Climate and Socio-economic Change

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

Some studies look at the effect of future climate change alone, assessing the risks on the current stock (and exposure and vulnerability). This is shown using a simplified illustration, starting with panel 1 (far left) below. However, in practice, even in the absence of climate change, there will be changes in exposure and vulnerability in the future, for example with the growing population projected in the UK, as well as the projected increase in economic growth. Panel 2 shows that even in the absence of climate change, future impacts could rise due to a greater stock at risk (all else being equal). However, it is not sufficient to add climate change and socio-economic together (Panel 3) because the two acting together can lead to larger cumulative risks (Panel 4, far right), e.g. climate change acts on a larger number of people or a greater value at risk (e.g. see Rojas et al, 2014). Ideally, therefore, studies should look at the future impacts of climate and socio-economic change individually as well as together, in order to separate out the relative importance of each, though in practice this is rarely considered in national risk assessments due to the difficulty of conducting this analysis across a wide range of risks.

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



Furthermore, they generate issues of attribution. When looking at future economic costs, due to the combination of climate and socio-economic change, some of these impacts would have occurred anyway. It is possible to get around this effect when looking at mitigation policy by directly comparing the economic costs of different climate futures, i.e. the difference between a 2°C and 4°C world, and looking at the change in economic costs.

These issues make the valuation extremely complicated, because if reporting estimates, one has to go back to original sources and try and work through what is included. It is stressed it is not possible to separate out socio-economic and climate signals from an original study, unless the authors have run a socio-economic only run alone (which is good practice, but normally omitted). Further, it is not possible (or certainly not easy) to introduce socio-economics into a primary study that has looked at climate change only (i.e. with static assumptions).

In this study we aim to be transparent on whether future socio-economic change has been included or not, and where possible show estimates with and without, but this is not possible for most risks.

Current Adaptation. The final challenges relates to the fact that the UK is now undertaking adaptation. In the CCRA3 method, this is assessed in Step 2. In an ideal analysis, the valuation would undertake a counterfactual valuation in Step 1 to establish magnitude, and then reanalyse future risks and opportunities after taking account of current and planned adaptation (noting this would also estimate the economic benefit of d adaptation). However, with the exception of a few areas (flooding and water plans) there is almost no evidence to allow such an analysis. Most of the valuation evidence is therefore presented without existing adaptation. We highlight that this may mean we overestimate economic costs.

It is stressed that while it would be desirable in theory to assess the economic costs of climate change as total and marginal, and gross and net of socio-economic change, and with and without current adaptation, this is extremely challenging in practice.

Discounting

The monetary valuation in CCRA3 has sought to impose some consistency through the use of a common base year for prices.

It has also reported future values without discounting (where possible), in order to facilitate direct comparison over time and between sectors.

However, it is stressed that the consideration of the economic costs of climate change in subsequent policy or project appraisal of adaptation, should discount.

The choice of discount rates has been a source of considerable disagreement in the literature, but this has been focused on the long-term values, notably in estimates of the social cost of carbon (SCC) (discounted sum of all future costs of climate change for a tonne of emission) or cost-benefit analysis of mitigation policy.

Such issues do not apply to most short-term adaptation. For longer-term adaptation investments, it is stressed that the UK guidance (HMT, 2020) already uses declining discount rates and further, there is supplementary guidance that allows use of intergenerational discount rates (HMT, 2008[xix]). It is highlighted that such considerations may be applicable when non-marginal risks occur in the UK, and for transformational.

Aggregate estimates

At the global level, previous studies have reported the aggregate economic costs of climate change in future years, as an equivalent % of GDP (Watkiss, 2011[xx]), noting this is different to the social cost of carbon which is the discounted sum of all future costs of climate change for a tonne of emission. The most famous of these is the Stern Report (2006)[xxi].

Most of the earlier global studies estimate a 1 to 2% welfare-equivalent income loss, expressed as a percentage of income, for 2 – 3°C of warming[xxii], although recent report higher costs for the same temperature changes, due to more negative literature on impacts[xxiii]. There are also a set of studies that derive much higher estimates of the economic costs of climate change, based on econometric based analysis[xxiv], partly because they assume climate change could reduce growth rates (rather than just output). However, some of the results of such studies do not look plausible, and as an example, they provide very odd results for the UK.

For CCRA3, we do not provide an aggregate estimate of the economic costs of climate change to the UK, nor express risks as a % of GDP. This is because it is very challenging to do such an analysis through a synthesis exercise. It is also important in that providing any such estimates, the total economic costs are presented, and not a sub-total (which is a problem, because there are many gaps in the evidence).

It is also noted that CCRA3 considers risks and opportunities, i.e. impacts and benefits. In global studies (and estimates of the %GDP equivalent) these are usually aggregated together, i.e. climate change is the net impact of gains and losses. For a UK study, we do not believe that such aggregation is appropriate, because it loses the importance of risks and the driver for adaptation, e.g. we look at reduced winter heating demand and increased summer cooling and report these separately: we do not add these together and look at the net economic effect.

Uncertainty

A final issue is around uncertainty. The economic costs of climate change vary because of the uncertainty around scenarios (i.e. the 2°C or 4°C pathway) but just as much, due to climate model uncertainty. These are both large, especially in the medium term of most relevance to policy considerations and adaptation.

The projected temperature and precipitation changes for the UK are broadly similar until the 2040s (and thus mid-century 2050) across all the scenarios, i.e. with similar results for RCP2.6, RCP4.5 and RCP6.0 and to a slightly lesser extent in results for RCP8.5. However, there is a much larger difference in the results between or within models at this time. This means that the main uncertainty at mid-century is due to differences between (and within) the climate models. This is captured by the 10th to 90th percentile range from UKCP18. This leads to a considerable range, and for some parameters (e.g. summer rainfall), it can even lead to a change in the sign, i.e. moving from an increase to a decrease in projected change.

This is illustrated in the figure below, with the effect of climate change on UK summer rainfall (from UKCP18 (Lowe et al., 2018[xxv]). This compares:

- RCP2/6 and RCP8.5 (scenario uncertainty);
- The 10th, 50th and 90th values from the probabilistic projections (model uncertainty).

The left-hand panel shows the projections for the 2050s. In this case, the model uncertainty dominates, indeed, there is not much difference between RCP2.6 and 8.5 (i.e. between a 2 and +4°C pathway). However, this uncertainty changes the sign of the change (i.e. whether a decrease or increase in summer rainfall). The right-hand panel shows the projections for the 2080s. In this period there is very large uncertainty from both scenario uncertainty (RCP2.6 vs 8.5) AND modelling uncertainty (10th to 90th).

This does matter. Even in the 2050s, the projected change of summer rainfall extends from a 34% reduction to a +2% increase. The central value is -15%. Reporting only the economic costs of a central value (15% reduction) does not convey the potential for downside economic risks. In the adaptation literature, including adaptation economics, this has led to a focus on decision making under uncertainty (Watkiss et al., 2014[xxvi]).

Where possible, and if they exist, we therefore report the importance of uncertainty for future economic costs.

However, for valuation, this uncertainty extends considerably. First, there are often quite large differences in impacts projected by studies, even for the same scenarios. This can result from the use of different impact functions or models, from different climate hazards (especially whether slow onset or changing extremes).

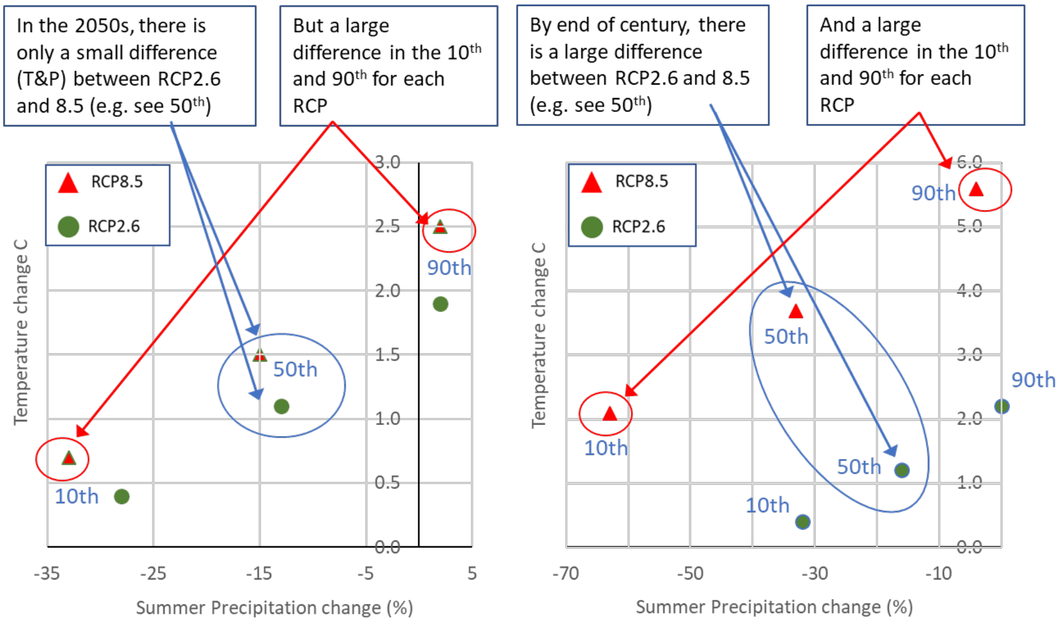


Figure 2 Plot of Temperature change versus Summer Precipitation – for (left) the 2041 – 2060 period and (right). 2080-2099,relative to 1981-2000 for RCP2.6 (green) and RCP8.5 (red) from left to right, for 10th, 50th, 90th. percentiles of the UKCP18 ensemble range. Note scale are different in the graphs. Source Lowe et al., 2018.[xxvii].

Second, there is uncertainty around the valuation estimates. This can arise over the choice of valuation endpoint, e.g. how to value deaths brough forward by air pollution, but it can also depend on the choice of economic analysis, especially when extending to partial equilibrium modelling and general equilibrium modelling. This includes additional price effects and starts to take into account the effect of changes elsewhere in the world. As an example, while yields of some crops may decline in the UK, there could still be positive effects for prices and exports, if yields decrease much more in other competing regions. This can lead to completely different results between the results of physical impacts and economic impacts.

Practical Approaches for CCRA3 Valuation

In CCRA3, different types of evidence haven taken for the monetisation as follows:

- For some risks and opportunities, direct economic cost estimates are already available (such as floods). In this case, these values will be used directly, after checking these are consistent with existing Government appraisal guidance.
- Where quantified risk information exists but no valuation has been undertaken, the approach will use unit values from existing Governmental appraisal guidance. This has been possible for a small number of risks.
- Where no quantitative information is available, estimates of the order of magnitude of the economic costs is made using available information and expert judgement.

When unit values are used, these are based on guidance from HM Treasury Green Book and Supplementary Guidance from Departments and Ministries, e.g. for transport, we would draw on the Department of Transport WEBTAG guidance on appraisal.

However, for many risks, no government appraisal guidance or unit values exist. In these cases, estimates are based on the literature. Ideally, these are based on valuation estimates from market values or willingness to pay estimates. However, where such data are not available, we use alternative approaches for valuation (e.g. repair or adaptation costs) to provide indicative estimates.

Adaptation

A new task included in CCRA3, at the request of the Customer Group, was to consider the possible costs and benefits of the further action identified. As set out earlier, valuation (monetisation) is a standard part of UK government policy development and economic appraisal, based on the principles of welfare economics. These same concepts are applicable to the identification of possible further adaptation interventions, and the analysis of the benefits of further action.

This task (3.2 of the CCRA3 method) investigated the indicative costs and benefits of the further adaptation action. This information was used to help identify the possible priority areas for action, to assess the possible benefits of further action as compared to costs, and to help inform the urgency score. Given the synthesis nature of CCRA3, this was based on a review of existing evidence and qualitative analysis.

It is stressed that the analysis of the costs and benefits of adaptation is challenging, much more so than for mitigation, and this makes it difficult to gather comparable information on further action across risks and opportunities. For mitigation, benefits are measured using a common burden (tonnes of GHG reduced), irrespective of location and sector, and many studies prioritise options using a cost-effectiveness analysis (£/tCO_2), which is a relative measure and provides direct comparability across interventions. This also makes it easier to use a synthesis exercise to gather information on benefits of further action. In contrast adaptation benefits require quantification of the reductions in climate impacts (not burdens), and these are time-, sector-, location- and context- specific. Adaptation is also generally introduced as part of a mainstreaming approach in the UK, which requires consideration of multiple metrics, not a single metric, and this means that a cost-effectiveness approach is insufficient. The economic prioritisation of adaptation is therefore better suited to cost-benefit analysis (CBA). However, because of uncertainty, as well as valuation in non-market sectors and of non-technical options, this normally requires extended cost-benefit analysis or multi-metric appraisal (see Chambwera et al., 2014[xxviii]).

There is also a very low evidence base on the costs and benefits of adaptation and many estimates in the literature are based on technical (engineering) adaptation options for long-term climate change (OECD, 2015[xxix]). For CCRA3, however, the focus is on the costs and benefits of short-term adaptation priorities (implemented over the next five years), which might have short, medium or long-term benefits. Given the synthesis approach of CCRA3, it was not possible to undertake new analysis, and thus the task drew on previous evidence reviews (ECONADAPT, 2017[xxx]) and available literature.

It is noted that the consideration of the costs and benefits of adaptation, as part of economic appraisal, does require the use of discount rates, in order to estimate the net present value or benefit to cost ratio. As highlighted earlier, the use of discount rates when calculating the social cost of carbon, or the costs and benefits of mitigation policy, has been contentious. However, CCRA3 is not looking at mitigation policy: it is focused on domestic adaptation, particularly near-term actions that align within the existing policy decision landscape and thus existing Government recommended discounting approaches. For longer-term adaptation investments, it is stressed that the UK guidance (HMT, 2018) already uses declining discount rates. It is also noted that CCRA3 still prioritises long-term adaptation considerations, with early action to plan for longer-term risks. However, it is highlighted that in future CCRAs, if transformational adaptation is identified, this may necessitate consideration of intergenerational issues when considering the costs and benefits of further action (and accordingly, the HMT intergenerational discount rate scheme, HMT, 2008[xxxi]).

Towards the end of the CCRA3 process, in late 2020, new HMT supplementary Green Book guidance was published on accounting for the effects of climate change (adaptation) (Defra, 2020[xxxii]). While this was too late to inform this CCRA3, the approach the guidance recommends broadly aligns with the description above.

Natural Environment

The list of risks and opportunities considered in the CCRA3 Technical report (Chapter 3), and thus for valuation, are presented below:

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

The monetary valuation of climate change risks for the natural environment, and their impacts on human welfare, is one of the most challenging areas. However, the main challenge is that there is little quantification of the risks of climate change, i.e. there is little physical impact evidence on which to apply valuation estimates. This means that the valuation of natural environment relies on a mix of qualitative and semi-quantitative evidence, case studies, and expert judgement, much more so than for other chapters.

Valuation is also challenging because the majority of the risks are not captured by market prices. Consequently, non-market measures of the willingness to pay to avoid impacts – or for positive impacts – are needed to understand effects on economic welfare.

In practical terms, studies to derive non-market value are not easy or cheap to obtain, relying usually on survey-based evidence or data that captures people's values through their behaviour (e.g. expenditures made to visit a national park, e.g. the ORVAL tool for valuing recreational visits to national parks and other greenspaces[xxxiii]). There is some literature on the economic values associated with valuation of the natural environment that has been assembled by international initiatives such as The Economics of Ecosystems and Biodiversity (TEEB, 2009; TEEB, 2010[xxxiv]), and through valuation databases internationally (the Environmental Valuation Reference Inventory, EVRI[3]) and in the UK (the Natural Environment Valuation Online tool (NEVO[4]) as well as the Defra ENCA[xxxv] and the Natural Capital Accounts developed by the ONS[xxxvi]. This provides potentially relevant information, but these estimates can only be used if there is quantitative information on the physical impact of climate change, to apply these values to.

Much of the valuation for the natural environment area is framed using the ecosystem service-based classification from the Millennium Ecosystem Assessment, i.e. Provisioning Services; Regulating services; Cultural Services and Supporting Services. This is shown below. These can provide estimates that could be transferred to the climate change context (through value transfer approaches), though there are some caveats here as the effects of climate change could be non-marginal, i.e. it might not be appropriate to use value transfer for the potentially very large changes that might occur.

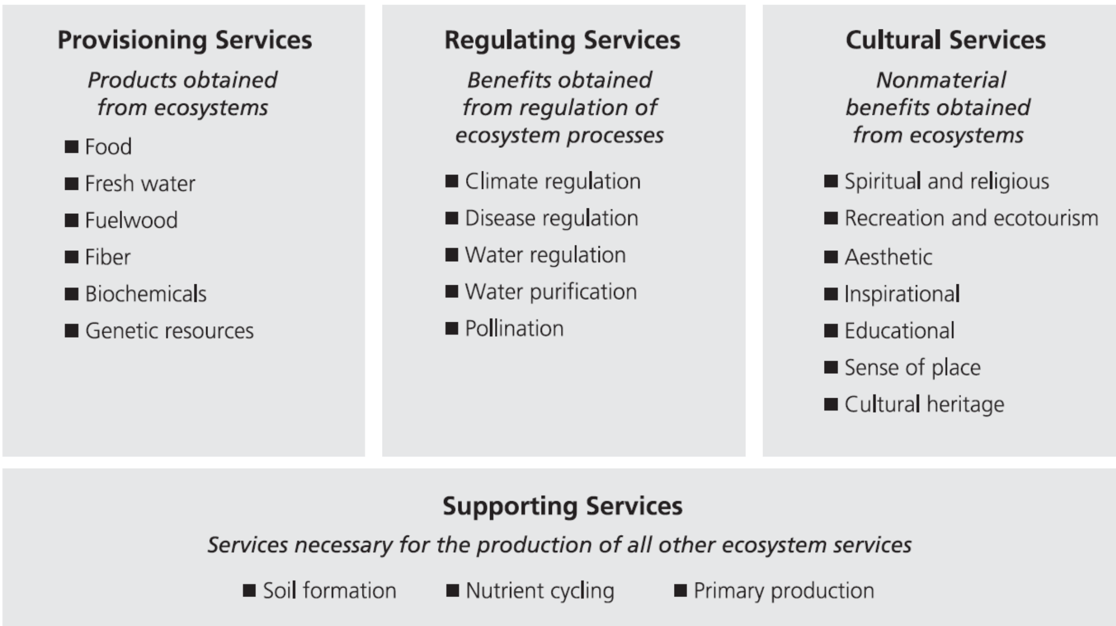


Figure 3. Ecosystem Services. Source Millennium Ecosystem Assessment.

There is also a further issue on the framing used and the need to capture the role of the natural environment as natural capital (see box below). Natural capital extends to focus on the stock of assets, and how their quality and quantity change, as well as the flows of benefits (of ecosystem services)[5]. However, the analysis of risks and opportunities in CCRA3 has not been quantified in terms of the potential effects on natural capital. Therefore, this chapter estimates the likely economic costs of individual risks of climate change, as much as data and evidence allows. A natural capital approach would focus on the impact of climate change risks on the quality and quantity of the stock of assets, or the total impact on all the benefits provided by a given natural capital asset. There has, however, been some consideration of natural capital in the CCRA Advice report.

[3] https://evri.ca/en/splashify-splash
[4] https://sweep.ac.uk/portfolios/natural-environment-valuation-online-tool-nevo/
[5] Natural capital also include abiotic as well as biotic elements of nature. A comparison of the two is available at https://naturalcapitalcoalition.org/wp-content/uploads/2019/06/NCC-WhatIs-NaturalCapitalApproach-FINAL.pdf

Box NE1. Natural Capital
Natural capital is defined by the Natural Capital Committee (NCC) (2017[xxxvii]) as follows: Natural capital are the elements of nature that directly or indirectly produce value to people, including ecosystems, species, freshwater, land, minerals, the air and oceans, as well as natural processes and functions. It is therefore the services that flow from the natural capital that we look to value in economic terms. Natural capital is a broad term that includes many different components of the living and non-living natural environment, as well as the processes and functions that link these components and sustain life. Natural capital assets include all biotic and abiotic assets (e.g. species, ecological communities, soils, freshwaters, land, atmosphere, minerals, sub-soil assets and oceans) and include both designated and undesignated habitats and species. The magnitude of a risk on a natural capital asset can be measured using any of the quantitative or qualitative indicators [of NCC 2017?], and not just those described using the term 'natural capital'.

For the valuation here, our approach has been to first consider which specific ecosystem services are relevant for each risk or opportunity, and then to consider if the evidence is qualitative or quantitative. However, we stress that this analysis does not capture all impacts: any estimates should be considered as partial unless stated otherwise.

Based on the approach of Hooper et al. (2014)[xxxviii] we then identify the human welfare effects of the risks, where evidence exists, and look at possible monetary data to express these. In doing so we consider whether existing market and non-market data can legitimately be transferred from its original context to the current climate change risk context (i.e. benefits transfer). The coverage of the estimates, and whether these are total or partial, or derived from a case study, are also reported.

This evidence is then used to provide an overall valuation range. In most cases, the confidence in the estimates (for the valuation) are low. The risks and opportunities are assessed in turn below.

N1 Risks to terrestrial species and habitats from changing climatic conditions and extreme events, including temperature change, water scarcity, wildfire, flooding, wind, and altered hydrology (including water scarcity, flooding and saline intrusion)

CCRA3 findings

Chapter 3 of the CCRA summarised the evidence on this risk. There is now considerable evidence of the current and likely future effects of climate change and associated drivers on individuals (e.g. their physiology and phenology), populations (composition and abundance) and species (distribution). These combine to affect community and habitat composition and thus the services that they can deliver (captured in Risks N6 and N18). These changes can lead to losses or gains of species in a community or geographic area, whilst changes in distribution can represent threats or opportunities for the receiving area (Risk N3). Risks are therefore different for different species and habitats, but given the potential for local or more widespread extinctions and losses, the current and future risks are both assessed to be high magnitude across the UK.

Valuation

The analysis of this risk is challenging because of the very wide coverage of all climate change-induced change to all terrestrial species and habitats. In turn, this means there is a very large number of potential effects on ecosystem services. However, many of these effects are covered in subsequent risks or opportunities, and thus there is a need to avoid double counting. It is also highlighted that climate change is not the only driver, and often not the most important, of species population change.

The linkages between ecosystem changes and effects on ecosystem services (and on human welfare) were not identified in the CCRA3 assessment. A supplementary literature review has been undertaken as part of this study, but this has not identified any quantitative estimates to welfare change resulting from the types of ecosystem changes described.

There, are, however, some examples that provide insights on the potential level of risks in monetary terms.

Most provisioning services are covered in later risks, but there are some additional risks to provisioning services associated with unmanaged natural environments. A clear example is pollination. By way of illustration, a recent assessment of the value of pollinators to crops in the UK reported an aggregated value of £620 million annually[xxxix]. A fractional decline in the scale of pollination – irrespective of socio-economic change – may therefore be in the order of £tens of million, annually. A survey-based study estimated the willingness to pay for the pollination services of bees in the UK, in the context of habitat destruction and climate change (Mwebaze et al., 2010)[xl]. The authors explored how much public support there would be in preventing further decline in the number of bee colonies in the UK. They found that the mean WTP to support a bee protection policy was £1.37/week/household. Scaling up to the 25 million households in the UK, this is equivalent to £1.77 billion per year. However, this is the total WTP and the prevented change attributable to climate change was not separated from other causes. The CCRA3 chapter also does not quantify the size of the potential effect on pollinators. Nonetheless, the evidence presented here indicates that the potential magnitude of climate risks might be high.

For cultural services, there will be direct use and non-use values (including option and existence values). There is some partial information on these from charitable donations. For example, there are estimates of the amount of money given to charities with a focus on the environment and conservation. The Charities Aid Foundation report on charitable giving in the UK (CAF[xli]) reports that the UK population donated £400 million to conservation, environment and heritage in 2018 – equivalent to £7.50 per household per year. This total provides some (albeit partial) information on the peoples' preferences to maintain the natural environment in its current state, though the inclusion of heritage inflates the estimate and it is not possible to disaggregate the natural environment or climate change portion. Moreover, it does not identify preferences relating to changes attributable to climate change, or the size of changes encouraged or to be avoided.

There are a small number of large-scale international assessments that provide some additional context. Tietjen et al. (2010)[xlii] used the Lund-Potsdam-Jena Dynamic Global Vegetation Model, which simulates the dynamics of both natural and managed vegetation grouped into plant functional types, and combined analysis of climate change effects with Willingness To Pay (WTP) results available from the published literature gathered in the TEEB database (McVittie & Hussain, 2013[xliii]). This was used to look at changes in ecosystem services, as identified from application of the vegetation model, and physical changes in biome coverage. It was therefore essentially a partial equilibrium ecosystem-economic modelling exercise, undertaken at the European level. Results for the different biomes under an A1B scenario were mixed, i.e. with negative impacts on some biomes such as desert/tundra and scrubland, and benefits for others such as mixed and temperate forests.

The OECD (2015)[xliv] undertook an assessment of the global economic consequences of climate change, with regional disaggregation (that included regions of Europe) using a computable general equilibrium model. They modelled changes in terrestrial mean species abundance as an indicator of biodiversity between 2010 and 2050. In order to value biodiversity loss, they adopted a function that related expenditure on environmental protection to temperature change under climate scenarios. The two climate scenarios adopted were RCP6.0 and RCP8.5. The cost estimates for (all) EU countries under these scenarios were 0.5% of GDP, and 1.1% of GDP, respectively.

The PESETA IV project (Barredo et al., 2020[xlv]) considered the impacts of climate change in European mountains, treeline shifts, including for England and Wales, Northern Ireland and the Scottish Highlands, and discussed potential changes in ecosystem services (hydrological properties, water quality, erosion protection and recreational services) but did not value these.

The COACCH project (COACCH, 2020[xlvi]) used GLOBIO, a scenario-based gridded global model for biodiversity, which estimates the Mean Species Abundance – an indicator of biodiversity – on the basis of a meta-analysis of a range of studies at the European level. The results found a negative impact of climate change on biodiversity. Plants were considered to be more sensitive than vertebrates (partly from a lower ability to adapt). The exact relationships are uncertain, but the analysis suggested a 25-30% decline in plant biodiversity for 4 degrees warming and a 10-20% decline in vertebrate biodiversity. Economic valuation was undertaken by utilising unit values per hectare. The results show annual damage costs in 2050 to range between about Euro 15 billion and Euro 22 billion for Europe under SSP2-RCP2.6 and SSP2-RCP6.0 scenario combinations, very approximately equivalent to 2 and 4°C pathways respectively, whilst for 2100 the range of annual damage costs are Euro 14 billion to Euro 58 billion. There is not sufficient information to break down these for the UK but on the basis of land area it suggests impact values of £100+ million annually.

Table 5 Climate Change-induced Biodiversity damage costs in Europe. Source COACCH, 2020.

Time Period	Scenario	Euro (bn, 2018 prices, annual)
2050	SSP2_2.6	14.9
	SSP2_3.4	18.4
	SSP2_4.5	21.0
	SSP2_6.0	21.9
2100	SSP2_2.6	14.0
	SSP2_3.4	23.6
	SSP2_4.5	38.5
	SSP2_6.0	57.7

Finally, an alternative approach that has been applied in the UK is to look at restoration costs for damaged habitats, as a proxy for damage. Berry & Hunt (2006)[xlvii] in the UK used a replacement cost approach to value changes in habitat coverage. A combination of literature review and SPECIES model outputs was used to identify species and habitats of national and regional significance, sensitive to climate change, including some which have a direct economic value. The SPECIES model simulated changes in suitable climate space at the national scale. It was run using A1F1 (high) and B2 (low) emission scenarios. The study used the restoration and re-creation cost data from the UK Biodiversity Action Plan (UK BAP), which were calculated by multiplying the estimates of the area degraded or lost by the annual costs. The results show £400,000 to £890,000 (2004 prices) for the 2020s and £1.6 million to £2.8 million in the 2050s, but it is stressed that these values are very partial in terms of coverage and valuation

The examples above cannot be taken to provide firm quantitative estimates, but they do illustrate that there is likely to be a potentially large economic welfare impact associated with risks to terrestrial species and habitats from climate change in the UK. On the basis of the review, it seems likely that these impacts are high (£hundreds millions/year), and quite plausibly very high (£Billions/year), but it is also clear that there is a significant lack of quantitative evidence.

Valuation summary

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Not known	Not known	Not known	Not known	Not known	Not known
England	Not known	Not known	Not known	Not known	Not known	
N. Ireland	Not known	Not known	Not known	Not known	Not known	
Scotland	Not known	Not known	Not known	Not known	Not known	
Wales	Not known	Not known	Not known	Not known	Not known	
Confidence		-	-	-	-	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation

The valuation of the impacts of climate change on terrestrial species and habitats is challenging, and this makes it difficult to analyse the subsequent benefits of adaptation in reducing these risks. It is also highlighted that while the literature on the costs and benefits of adaptation is improving, there is very little information on the costs and benefits of helping natural systems adapt (Tröltzsch et al., 2018[xlviii]). There has been some analysis on the costs and benefits of peatland restoration (Moxey and Moran, 2014[xlix]; Bright, 2017[l], Watkiss et al., 2019[li]), which indicate that restoration is generally worthwhile in most (but not all) cases, for both upland and lowland peatlands (i.e., with positive benefit cost ratios). The benefits increase if more ecosystem services are able to be valued (and this is a general issue for many risks in this chapter) and climate change strengthens the case for restoration. There are some case studies on cost-effectiveness or cost benefit analysis of buffer zones, migration corridors and even translocation for specific habitats or species (e.g., Tainio et al., 2014[lii]) though this remains a gap (especially on the benefits analysis). Finally, there would seem to be a strong economic case for an expanded role for Government intervention to provide enhanced monitoring and surveillance and early response.

N2 Risks to terrestrial species and habitats from pests, pathogens and invasive species

CCRA3 findings

Chapter 3 of the CCRA Technical Report summarised the evidence on this risk. It reports that while there are international and national policy frameworks for managing the risks to terrestrial species and habitats from native pests and pathogens, including Invasive Non-Native Species (INNS), these risks are expected to continue increasing. Changes in these risks are primarily influenced by socioeconomic drivers, including cross-border trade, within-country movements, biosecurity measures and land use change, i.e. climate change is generally considered a second order influence. Evidence of recent increases in the number and severity of outbreaks of native pest and pathogen species, and establishment of INNS, indicate that risks to terrestrial species and habitats have continued to increase since CCRA2. Warming is likely to expand the range of climate suitability for many species and increase the chance of establishment of INNS in the UK, particularly for species that have shown recent northward expansion across Europe.

Valuation

N2 involves potential risks to regulating, provisioning and cultural services. This risk categories covers a large number of potential species, and this makes it difficult to produce an aggregate risk. However, most of the quantitative evidence exists for the risks to provisioning services, and thus the potential risks of pests, pathogens and invasive species to agriculture, forestry and fisheries. These are considered in N7, N8 and N16 and are not repeated here in order to avoid double counting.

The focus for this risk is on the impacts of pests, pathogens and invasive species to regulating, supporting and cultural services. The evidence base here is extremely low, in terms of quantitative effects, and subsequent implications for these ecosystem services. It is certainly possible that they could be large, but this is reported as ‘not known’ because of this lack of primary evidence.

Valuation							
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Not known	Not known	Not known	Not known	Not known	Not known
Confidence	Very Low	Very Low	Very Low	Very Low	Very Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation
There is a strong economic case for greater Government intervention in research, monitoring, awareness raising and coordination of reactive response to potential and emerging threats (including invasive species) based on case study analysis of four major pests and pathogens Phytophthora ramorum, Ash dieback, Dothistroma Red needle blight and Septora, a winter wheat yellowing fungus (see Watkiss et al., 2019[liii]). Although this would require additional Government action, Watkiss et al. (2019) project that the economic benefits are high compared with the costs. There is a clear a role for public co-ordination of research, monitoring and surveillance. Previous analysis by SRUC (2013[liv]) has identified that investment in monitoring for pests has a high benefit-cost ratio of around 10:1. There are also clear benefits from Government investing in information about pests and pathogens – their spread, likely impacts, and treatment methods – as this information flow would not otherwise occur. Whilst a large proportion of the costs (or pests and pathogens) may be borne by private land-owners, public support is likely to be needed where there are local concentrations of economic activity that are threatened by the rapid spread of one of these pathogens in an area (to reduce the much larger costs once pests and pathogens become established). This economic argument is strengthened by climate change because the future nature of the threats will be less understood by private actors' past experience.

N3 Opportunities from new species colonisations in terrestrial habitats

CCRA3 findings
Chapter 3 of the CCRA Technical Report summarised the evidence on this risk. Opportunities of climate change will be taxon and species specific, with more mobile species likely to be more responsive. Climate change, especially increasing temperatures, can provide the opportunity for increases in populations, as well as leading to species moving and / or expanding their ranges northwards or to higher altitudes. Thus, they have the opportunity to colonise new areas. This can take two forms, firstly the species can be new to the UK, although the level of migration is restricted as these are islands. If it interacts negatively with native species, or alters habitat condition, then it is considered an INNS (Risk N2). Secondly, the species may be new to an area, be it a Devolved Administration or a region. Climate, however, is only one of a number of interacting factors that will affect the ability of species to realise the opportunity presented by increased suitable climate space. Dispersal potential may be limited by lack of dispersal routes and suitable habitat availability.

The CCRA3 Technical Report does have some quantitative information:

- A simple analysis (based solely on climate) of 3,048 species from a range of taxa, compared projected future distributional changes with recently observed changes and found that, under a 2℃ warming scenario, climate change could represent a medium or high opportunity for 54% species in Great Britain (Pearce Higgins et al., 2017).
- Modelling of changes in suitable climate for birds under the future 3°C-rise scenario projected that, some birds (such as melodious warbler, short-toed eagle, red-backed shrike, short-toed tree creeper) potentially could establish (or re-establish) regular breeding populations in Britain in the next few decades at least partly as a function of climate (Ausden et al., 2015; Hayhow et al., 2017).
- Massimino et al. (2015) model changes in climate suitability for 124 bird species in Great Britain using the UKCP09 SCPs and a medium-emissions (A1B) scenario and showed increases for 44% of species by 2080, with 15% of species projected to increase by 2080 currently red-listed (high conservation concern) and 13% amber-listed (medium conservation concern).
- There is also some evidence that for some species of butterflies there could be positive benefits, and also for some rare species. These positive effects need to be seen in the context of the negative impact discussed elsewhere, but they indicate there could be benefits for some species.

Valuation
It is difficult given the low availability of evidence to develop valuation estimates for this opportunity. There are likely to be values attached to some cultural services associated with positive bird and butterfly species changes, as identified above, however, there is insufficient quantitative data on the physical change and also challenges for subsequent valuation of these. It is therefore difficult to

judge what the positive effects might be, and in aggregate, because of the lack of quantitative impacts information, and the link to services.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Not known	Not known	Not known	Not known	Not known	Not known
Confidence	-	-	-	-	-	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation

The potential size of the opportunities involved are not well characterised, and this make it difficult to assess the potential costs and benefits of adaptation: a low regret option would therefore be to investigate these potential opportunities, and to consider what steps might be needed to help realise the more important.

N4 Risk to soils from changing climatic conditions, including seasonal aridity and wetness

CCRA3 findings

Chapter 3 of the CCRA summarised the evidence for this risk. Climate parameters influencing soils include temperature, (notably through soil temperature and net primary productivity); precipitation and evapotranspiration which influence soil moisture, water leaching etc.; and wind, which can interact with specific soil textures. Soil degradation can occur from erosion (water and wind), compaction, modification of water-holding properties notably by drainage, loss of soil organic matter (and soil organic carbon SOC), loss or modification to soil biodiversity, imbalance of nutrients, release of legacy contaminants into water bodies, and soil sealing. Climate change potentially could have some benefits for soils through enhanced net primary productivity (from temperature increases and elevated CO_2) and increased organic matter, but this will also be affected by temperature-related changes in decomposition rates. However, there are notable difficulties in differentiating climate change effects from other factors: many risks to soils are the product of climate-related processes acting together with socioeconomic factors to cause soil degradation, notably land use and land management. CCRA3 did not identify quantitative studies of potential impacts, but did consider the overall magnitude of the risk to be important.

Valuation

The importance of effective soil management – and soil quality - derives from the fact that soil performs several important functions: it supports food production, water storage, biodiversity conservation and carbon storage. This therefore means it provides provisioning, regulating and supporting ecosystem services. The ability of soil to perform these services is reduced when it is degraded (its quality is reduced) or eroded (its quantity is reduced), as can arise from several factors, which includes climate change. Climate change can potentially impact on soil quality through a number of pathways (Morison and Matthews, 2016[lv]):

- Soil degradation (although this can include multiple processes, including those below);
- Soil erosion (from heavy precipitation and extremes);
- Higher rainfall increasing soil compaction;
- Loss of soil organic carbon;
- Multiple climate factors affecting vegetation cover and soil processes, affecting function, water holding capacity, salinization, etc.

While estimates of carbon stocks are relevant for this risk, it is important to avoid double counting with the next risk (N6) on carbon stores. The valuation of carbon emissions is discussed in the box below.

Box NE2. Valuation of carbon emission

The monetary valuation of greenhouse gases (GHGs) can be estimated in relation to the economic impacts of climate change. These values can be used to report the aggregate economic costs of climate change. They can also be used to assess the marginal economic cost of GHG emissions, which can be used in the economic appraisal of new policies or projects. In theory, the relevant metric is the marginal damage cost of a tonne of emissions, known as the Social Cost of Carbon (SCC). However, estimating these economic costs of climate change is extremely challenging and while estimates are improving, there remains a wide range, which also depends on the discount rate and equity assumptions used. As a result, many organisations use a shadow price of carbon (SPC), as an alternative to the SCC (though these are usually based on the costs of abatement with respect to future targets, and the values are generally lower than the SCC). The UK Government has a long tradition of using carbon prices in policy appraisal, going back almost two decades (See Watkiss and Hope, 2011[lvi]). The UK government has agreed a set of carbon values that are to be used in policy appraisal and evaluation, and published as part of the Green Book Supplementary Guidance (BEIS, 2019[lvii]). More information is available at https://www.gov.uk/government/collections/carbon-valuation--2. These are based on the traded (EUA permit prices) and Non-traded sector (using the non-traded price of carbon).

The most direct climate pathway is from soil erosion, which leads to the reduced productivity and reduced soil carbon (and increased GHG emissions) and can also lead to downstream impacts such as on water quality. There are other impacts, though these involve complex pathways where climate is only one of many factors. Note that there are also some potential positive effects as well, from climate change increasing organic matter (although this is still the subject of discussion) and higher primary productivity. It is stressed, however, that in all cases, the overall scale of negative impacts and any positive effects will be dominated by land management.

There is some valuation information available on current risks. There is a literature which reports on the impacts and economic costs of soil erosion and land degradation, relating this to the reduction in (long-term) agricultural productivity, with values that are estimated at several % of agricultural GDP.

Graves et al (2015[lviii]) estimated the annual costs of soil degradation in England and Wales at between £0.9 and £1.4 billion. This resulted from erosion that includes: (i) the onsite costs of the decline in agricultural and forestry yields caused by the reduction in soil depth, the cost of a reduction in the stock of carbon, and the cost of replacing losses in Nitrogen, Potassium and K, and (ii) the offsite cost associated with impacts on environmental water quality, drinking water quality, and iii) greenhouse gas regulation. The total annual cost of erosion in England and Wales for all soil-scapes was estimated at about £177 million yr. Onsite costs (£40 million per year) comprise loss of yield potential, valued at market prices, and loss of soil nutrients, valued by their replacement costs. Offsite costs (£137 million per year) comprise mainly the treatment cost of nutrient removal from drinking water, the damage costs of nutrients passing to the water environment, sediment removal from rivers and lakes and sediment removal from urban drainage systems.

The cost of compaction was considered by Graves et al. (2015) to include: the onsite cost of agricultural and forestry yield decline caused by impaired rooting medium and reduced water holding capacity, the extra draught power associated with ploughing and cultivation operations, and the cost of losing applied N, P, and K because of extra runoff. The off-site costs included the impact of compaction induced additional N, P and K in the water environment and the environmental burdens associated with increased soil tillage. An estimated 3.9 million ha are at risk of compaction in England and Wales, highest on clay soils during wet periods. The estimated total current cost of compaction is £472 million per year, about half of which is on-site, and half is offsite.

The loss of soil carbon has both onsite implications for agricultural production and offsite implications for global warming. Soil organic matter, for which soil organic C is a proxy, is critical for good soil structure. The annual cost of the loss of organic matter in the soil as measured by loss of organic carbon was calculated to be £3.5 million per year, based on the cost of replacing it with organic manures. The off-site cost in terms of GHG emission was much larger. Using the ratio of 1 to 3.67 for soil C to CO_2 in the atmosphere, the central estimated annual cost, assuming a CO_2 value of £51

CO_2e/t is £566 million mostly associated with clay and peat soils, ranging between low and high estimates of £360 million and £700 million per year respectively.

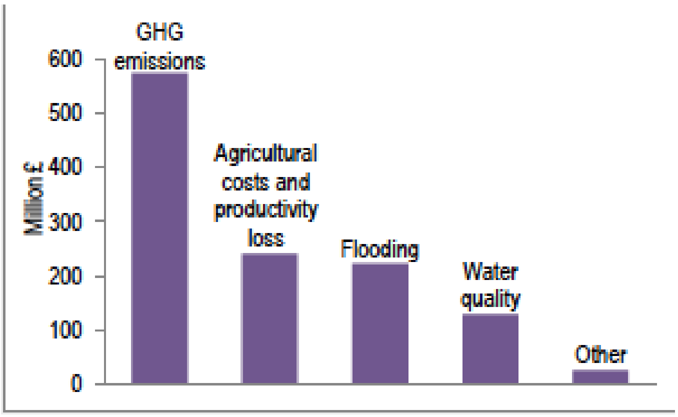


Figure 4 Annual costs of soil degradation in England & Wales. Source: POST, 2015[lix]).

In Scotland, the total costs of soil erosion including drinking water treatment have been estimated at £31-50 million/year (Rickson et al., 2019). The key challenge is to attribute current impacts to climate variability and extremes and then consider how future climate change might affect these current losses - a more difficult challenge. Some studies have projected that the impacts above could increase with climate change, primarily due to changes in rainfall (with estimates of a 20% increase in soil erosion by the end of the century, Cooper et al., 2010). In the medium-term (2050s) there is not much difference in the average and extreme rainfall projected under 2 versus 4°C pathways, but there is a very large difference due to model uncertainty and variability. As these indicate that rainfall projections for England could vary significantly, even in the sign of change, there is considerable uncertainty in the exact changes.

While there are no robust estimates of the future economic costs of climate change on soil degradation, erosion and compaction, it is possible to provide some indicative estimates by deriving annual totals for the climate change impacts. For example, applying the 20% change identified from the impact of climate change on erosion (Cooper et al. (2010) to the current economic costs of soil degradation presented above (from Graves et al. (2015)) would indicate potentially large economic costs, i.e. annual economic costs of £hundreds of millions/year (though these would be dominated by GHG emissions). The pathways for other climate change effects on soil, including vegetation cover and soil processes, and the effects on soil health, are not sufficiently well understood to project the detailed monetary effects of climate change.

A similar order of magnitude is derived from the study of Jones et al. (2020), which present estimates of the yield losses, and their value, associated with soil erosion. Their results are disaggregated for the four UK countries. Yield losses are one component of the onsite costs identified in the Graves et al. (2015) study. Indeed, they comprise approximately 2% of the total costs of soil erosion. In order to make use of the disaggregated and projected estimates of Jones et al. we therefore scale them on the basis of the more comprehensive Grave et al. estimates. We derive values for Wales separately by apportioning the combined England & Wales totals from Graves et al. on the basis of arable area in the two countries. Note that for England, the 4°C total costs are less than the 2°C costs. This is due to the relative change in rainfall intensity in regions with higher or lower arable area. Those with the largest arable area such as East of England and the East Midlands are regions where the increase in rainfall intensity is projected to be lower in the 4°C scenario later this century than in the 2°C scenario.

Table 6 . Soil Erosion Costs under current and future scenarios (£m, 2020 prices) Source, authors, updating and extending Jones et al., 2020 using estimates from Graves et al., 2015.

	Current	2°C	4°C
England	123	393	305
NI	0.5	1.0	9.8
Scotland	4.9	4.9	14.8
Wales	8.9	30.0	21.6

It is also possible to estimate the impacts of soil erosion in terms of loss productivity (the value of the lost crop production valued at market prices, with future losses discounted by market interest rates), and some studies have used restoration costs. Not surprisingly, the aggregation to national level involves many assumptions, and there are important issues with the boundary of the analysis (not least because upstream soil erosion can sometime lead to benefits downstream).

Interestingly, there is a study (GFSP, 2017[lx]) which has identified unlikely but plausible major tipping points for areas of England, from the impact of climate change on soil erosion leading to major production losses. The study is qualitative but indicates that the impacts may be very high, but this is considered a low likelihood, high impact event.

Valuation summary

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
England	High	High	High	High	High	
N. Ireland	Medium	Medium	Medium	Medium	Medium	
Scotland	Medium	Medium	Medium	Medium	Medium	
Wales	Medium	Medium	Medium	Medium	Medium	
Confidence		Low	Low	Low	Low	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation

Research is now increasingly available on the cost effectiveness of different soil protection measures, which can be applied for as assessing adaptation actions, although the distinctive properties of UK soils require that analysis is not simply transferred from other countries but is instead developed through a procedure that is consistent with the UK context. Investments in soil monitoring would seem a low-regret adaptation and a necessary precursor for subsequent improvements. As discussed in more detail for Risk N6, further investment in climate services (seasonal forecasting etc.) for agriculture and forestry, in conjunction with technological advances (e.g. precision agriculture) and improved management practices may have considerable benefits in averting and redressing many of the current negative outcomes for soils.

Economic analysis of soil protection and climate smart agriculture generally indicates positive economic returns, although financial returns from a farmer rather than societal perspective may be limited or take longer to accrue, and include non-market or off-site benefits (Kuhlman et al., 2010[lxi]; Watkiss et al., 2019), indicating also the key role of policy support. For individual practices, measures are often highly site-specific, as reflected in large benefit-cost ratios for similar interventions in different places, and evidence on these practices as viable standalone adaptation strategies remains limited and sometimes contradictory depending on assumptions (e.g. relationship with other measures) and context. Posthumus et al. (2015[lxii]), using an ecosystem services valuation approach, found that for soil erosion, use of tramline management, mulching, buffer strips, high-density planting and sediment traps were the most cost-effective control measures, with contour ploughing also cost-effective in some circumstances. However, the study also noted that assessments of effectiveness really need to be made at farm level or field level, because of the wide variation in biophysical and land use contexts, emphasising again the key role of outreach and guidance in stimulating proactive adaptation actions on the ground.

Previous analysis for CCRA1 and CCRA2 (Frontier Economics, 2013[lxiii]; SRUC, 2013[lxiv]) found uptake in the UK farming community and knowledge of the benefits for such measures was relatively low. For example, adaptations analysed by SRUC (2013) (with one exception, for cover crops) generated positive NPVs. These did not require long lead times and had positive ancillary benefits, but the study still identified the challenge would be to encourage farmers to adopt them. All of this suggests that while sustainable soil management approaches have potential for reducing climate impacts, their uptake requires these barriers to be addressed, and may need a combination of awareness and incentives to realise (Watkiss et al., 2019) though there are obvious opportunities to provide additional incentives through revision of the current farm payment schemes. There is considerable work also happening on soil management as linked with Net Zero pathways and it would therefore obviously be beneficial to increasingly link adaptation assessments with that research.

N5 Risks to natural carbon stores and sequestration from changing climatic conditions, including temperature change and water scarcity.

CCRA3 findings

Chapter 3 of the CCRA Technical Report summarised the evidence on this risk. This highlighted that confidence is low in assessing future change due to limited evidence and sometimes contrasting findings. These are due to complex spatial variations in GHG flux relative to local biophysical and land use settings, including the possibility of threshold effects, and differences in analytical methods. Climate warming will interact with spatial variations in aridity (risks to soils and vegetation stocks) and/or wetness (potential opportunities in some regions) to influence outcomes in terms of risk/opportunity in conjunction with land use decisions. These decisions include changes within agriculture, but also between these land uses as strongly influenced by policies for the Net Zero commitment.

Valuation

This is one area where the valuation step is relatively easy, as it can use the UK Government carbon prices discussed in the previous risk. The main problem is therefore the underlying evidence on the quantitative risk to carbon stores.

The context for this risk is that gross carbon sequestration of UK natural habitats was estimated to be 28 billion tonnes in 2017 (UK Natural Capital, 2020[lxv]). Applying the carbon values identified discussed in Box 2 (non-traded prices), this provides a service worth £1.92 billion yearly and an asset valuation of £108.7 billion. However, this excludes the emission costs related to the management of natural habitats. In 2017, forest land removed 18.0 million tonnes of carbon, equating to a value of around £1.19 billion annually and an asset valuation of £53.9 billion. In contrast, cropland emitted 11.4 million tonnes as a result of the loss of carbon stock when converting grassland to cropland. This means UK croplands provide negative net carbon sequestration valued at a loss of £0.76 billion annually, with an associated fall in asset value of £71.5 billion.

Blue carbon is not currently included. Using estimates of UK seagrass cover and recent carbon trading values it has been estimated that the total value of the seagrass standing C stock is between £2.6 million and £5.3 million (Green et al., 2018).

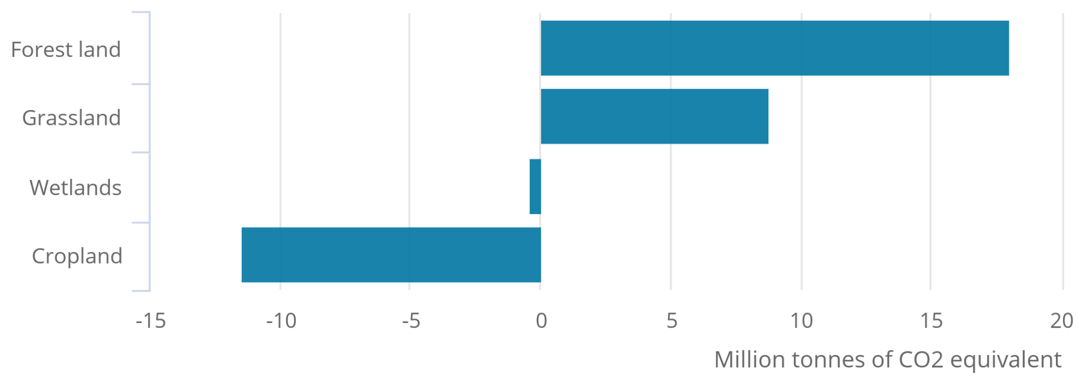


Figure 5 Net Sequestration, UK 2017. Source. Natural Capital Accounts, 2020.

The greenhouse gas associated with soil degradation was set out in the previous risk. The focus here is therefore on carbon sinks, and the effects of climate change on them.

The National Ecosystem Assessment (NEA (2011[lxvi])) provided estimates of the land cover in the year, 2060, based on various socio-economic scenarios. AECOM (2015[lxvii]) selected three of the NEA scenarios and used Bradley et al. (2005) 'land types' to assess the effect of land cover changes on carbon stocks in both: a) the soil, and b) the vegetation. By using a land cover dataset that also accounts for the indirect effect of climate change, this study quantified how climate change impacts, such as increased drought events or the abandonment of agricultural land, drive changes in land cover and thus changes in carbon stock. The three NEA scenarios used in AECOM (2015), reflect different societal attitudes towards the environment. These range from a society relatively concerned with the surrounding environment ('Local stewardship'), to one mainly concerned with trade ('World markets'). The 'Green and pleasant land' scenario is one where the conservation of traditional landscapes is a dominant driving force in society.

Each socio-economic scenario was matched with two climate change scenarios: 'low' and 'high'. These are loosely based on the results for mean temperature and precipitation changes under the UKCP09 low (SRES B1) and high (SRES A1FI) emissions scenarios for 2050–2079, (AECOM, 2015). These low and high scenarios are projected to drive changes in global mean temperature of +1.8°C (likely range +1.1 to +2.9°C) and +4.0°C (likely range +2.4 to +6.4°C) respectively (IPCC 2007). UK NIR (2014) assume that it will take anything from 50 to 750 years for a land cover change to be reflected in the soil carbon stock of the area in question (Table below), and as a rule of thumb, losses are often assumed to occur over shorter timescales than gains - principally due to disturbance of the soil. The AECOM (2015) study estimated the monetary value of changes in carbon stored in soil and vegetation stocks under the range of climate scenarios over the period 2010 to 2060. Thus, the annual change in tonnes of CO_2 equivalent was multiplied by the central non-traded DECC carbon prices for the period 2010 to 2060. These values were then discounted using a rate of 3.5% for the first 30 years and 3.0% thereafter in order to estimate the Present Value (PV) of the change.

The resulting changes in carbon stock levels for England are presented below. AECOM, (2015) found that 'Local stewardship' and 'Green and pleasant land' appear similar in policy terms and both result in substantial gains in soil carbon throughout lowland Britain. However, the areas of highest gains identified under each scenario are substantially different. In 'Local stewardship', the highest gains come in upland periphery areas, where afforestation and changes from improved grassland to semi-natural grassland drive a long-term increase in carbon amounts.

Table 7 Present Value of soil carbon stocks from 2010 to 2060 (£ billion, 2019 prices, updated from original study using BEIS carbon values[lxviii]).

	NEA Scenarios					
	Low Climate Change			**High Climate Change**		
	Local Stewardship	Green & Pleasant Land	World Markets	Local Stewardship	Green & Pleasant Land	World Markets
England	47	82	-71	52	107	-62

In 'Green and pleasant land', the largest gains come where the potential for habitat restoration is high: in the mountainous areas where substantial reversions of enclosed farmland to semi-natural habitat are projected for this scenario. The large difference between the low and high climate scenario versions is driven by an increase in semi-natural grassland under high climate, which generally replaces enclosed farmland in England.

In 'World markets', broad-scale industrialization of farming results in large net losses in soil carbon as more semi-natural and wild habitats are brought into cultivation. Unlike the other two NEA scenarios, for 'World markets' there is estimated to be less change to soil carbon stocks under high climate change than under low climate change. This is due to increased losses of arable land to higher temperatures, leading to increased drought and abandonment of unproductive land. Thus, reversion to woodland or semi-natural grassland reduces estimated loss.

The results suggest that the total value of the change in soil carbon stocks across England over the period 2010 to 2060 ranges from a low of -£33 billion in the 'World markets' (low emissions) scenario, to a high of £50 billion in the green and pleasant land (high emissions scenario).

These results equate to undiscounted, annual, totals of approximately (minus) £1 billion to (plus) £2 billion – a mid-point of these appears to be broadly consistent with the current annual loss of carbon of £566 million for England and Wales, as estimated by Graves et al. (2015); equivalent to £480 million for England alone.

This range of values is supported by Jones et al. (2020) who estimate the costs of excess carbon emissions as increased temperatures are projected to result in degradation of peatlands and reduced potential for carbon sequestration. They find excess annual costs of £1.1 billion in 2050s and between £1.5 billion and £2.2 billion in 2080s for the UK. These costs are primarily as a result of peatland in Scotland (70%), 15% in England, 10% in Northern Ireland and 5% in Wales. On the basis of the information presented in the previous paragraphs we provide an assessment of potential magnitude scores. Given the lack of quantification of a number of potentially significant risks to soil, these estimates should be regarded as conservative.

There is more detailed information available for peatland; it is a separate category in the ONS Natural Capital accounts, from which services flow[lxix]. The majority of peatland sites in England are primarily in poor condition as a result of land management practices, leading to areas of bare peat, a loss of soil, habitats and biodiversity, and reduced capacity to stabilise base and peak flows of water (Thomson et al., 2018[lxx]). In this condition, climate change will increase the loss of ecosystem services from peatlands including through the risk of loss of the peat-forming sphagnum moss layer on upland peats from hotter, drier conditions. Intact, functioning peatlands may still be susceptible to climate change, but evidence suggests that they will be more resilient (to it) and may indeed be able to self-adapt (e.g. through changing their vegetation species mix) to continue functioning. The difference in impacts between 2°C and 4°C pathways is difficult to specify, but it is presumed that degradation risks and rates of degradation increase with temperature and that trigger points, such as prolonged droughts or simply more variable patterns of precipitation, may well exist for abrupt shifts in vegetation cover and erosion (see Moxey, 2019[lxxi]). Ultimately, once a site approaches complete depletion of peat, degradation becomes irreversible. Before this point is reached, degradation can generally be reversed, albeit that required actions may be more expensive and take longer to take effect. This suggests that inaction now may potentially lock-in irreversible damage at some sites, and is more likely to incur additional on-going ecosystem service losses and increase later restoration costs.

The costs of inaction equate to the value of ecosystem services lost due to continuing and worsening degradation. Information on these costs is increasing as more studies are published, though the data remains incomplete. Consequently, given heterogeneity of site conditions and current management, it is difficult to estimate aggregate costs. Nevertheless, it is possible to use illustrative figures to give an indication.

In relation to climate regulation services resulting from peatland, the Peatland Code provides estimates of GHG emissions for different categories of degraded upland peatlands, ranging from around 2t CO_{2e}/ha/yr for lightly degraded sites through to around 24t CO_{2e}/ha/yr for actively eroding bare peat, with emissions from intensive cultivation or grazing of lowland peats being around 18 to 24t CO_{2e}/ha/yr (Evans et al., 2017[1]). Evans et al. (2016) estimate current annual emissions for English peatlands as around 11mt CO_{2e}. If published non-traded central carbon values[1] and the standard 3.5% discount rate are applied to these, the implied Present Value costs to 2040 are around £13.7bn without further degradation. If climate change causes annual emissions to increase by 0.5% to 1.5% per year, as assumed by Thomson et al., (2018[lxxii]), costs would rise to between £14.5bn and £16.2bn respectively.

There figures are, of course, sensitive to a number of underlying assumptions but give an indication of the possible magnitude. Arguably, under a 4°C+ scenario, rapid degradation of all unrestored sites might be expected to be triggered, pushing emissions to the upper-bound estimates more quickly and hence increasing overall carbon costs. In addition, given that current carbon price projections relate to 2°C scenarios, overall costs would presumably increase through unit-price effects as well as overall emission levels (but no such price projections appear to have been calculated).

Valuation summary

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	High	Very high	Very high	Very high	Very high	Not known
England	High	Very high	Very high	Very high	Very high	
N. Ireland	Medium	High	High	High	Very high	
Scotland	High	Very high	Very high	Very high	Very high	
Wales	Medium	High	High	High	Very high	
Confidence		Low - Medium	Low–Medium	Low - Medium	Low - Medium	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation

Restoration is a low regret action for degraded peatlands (CCC, 2013[lxxiii]), with early action having short-term benefits as well as longer-term resilience to climate change. Moreover, early action is desirable given that restoration to a near-natural, fully-functional state can take decades or longer and that restoration costs increase with the degree of degradation faced. There has been some analysis on the costs and benefits of restoring peatlands and enhancing carbon storage (Moxey and Moran, 2014; Bright, 2017, Watkiss et al., 2019), which indicate that restoration is generally worthwhile in most (but not all) cases, for both upland and even lowland peatlands, especially if a broader range of ecosystem services are included (Glenk and Martin-Ortega 2018[lxxiv]). However, these assessments are largely yet to include climate risks and the need for adaptation in achieving these objectives, and also the timing of costs and benefits. In particular, capital investment costs are incurred upfront whilst benefits accumulate more slowly over time (as do any opportunity costs). This makes the choice regarding both the time period over which comparisons are made, and the discount rate by which future costs and benefits are translated to an equivalent Present Value, important. Information does indicate that reliance on voluntary enrolment (rather than regulatory obligations) is likely to limit restoration, because of necessary capital investments but also interactions with (especially) agricultural policy support and market returns (the latter gives rise to high opportunity costs for productive lowland sites), and suggests further action will need incentives.

Economic assessment of carbon storage and GHG issues for other soils, and for the marine sector (wetlands and blue carbon) as a whole remains less available. Forestry is discussed in Risk N6.

N6 Risks to and opportunities for agricultural and forestry productivity from extreme events and changing climatic conditions (including temperature change, water scarcity, wildfire, flooding, coastal erosion, wind and saline intrusion).

CCRA3 findings
Chapter 3 of the CCRA Technical Report summarised the evidence on this risk. Both risks and opportunities are related to the type of farming or forestry, notably choice of crop, livestock or tree species (and specialist cultivars), and the spatial and temporal dimensions of the climate effects that correspond with different magnitudes of climate change. The interaction of multiple climate parameters with other biophysical and socioeconomic factors, including the current plans for Net-Zero GHG emissions, means future assessment inevitably involve some uncertainty.

Valuation
For the valuation analysis, this risk has been split into the agricultural and forestry sectors, and are reported as two separate scores.

Agriculture
Climate change has the potential to affect the agricultural sector, both negatively (e.g. from lower rainfall, increasing variability, extreme heat) and positively (e.g. from CO_2 fertilization, extended seasons). These effects will arise from gradual climate change and extreme events that will directly affect crop production, but will also have indirect effects, e.g. via the prevalence of pests and diseases. These various impacts will affect crop yields and in turn, agricultural production, consumption, prices, trade and decision-making on land-use (change).

Most studies take outputs from climate models and use these in crop growth models or statistical models to assess changes in yields. These can then be fed into bio-economic models, partial equilibrium (PE) or computable general equilibrium (CGE) models. PE models focus on land-based sectors only, but have more detail. CGE models can assess impacts on other sectors via income and price effects. This suite of models can also be used to assess some adaptation options (farm level options and trade). Only a few models also analyse the effects of extreme weather events, and this can make a large difference to results.

Importantly, results can change significantly when using economic models rather than crop models, because of the subsequent impact on productivity, land-use decisions, trade, etc. This can also mean there are cases where climate change might reduce yields in the UK, but the impacts of climate change in other countries on yields are even greater (e.g. in Europe or globally). When these other changes are factored into the analysis, with trade and price effects, this can lead to positive economic benefits for UK producers (if they respond accordingly).

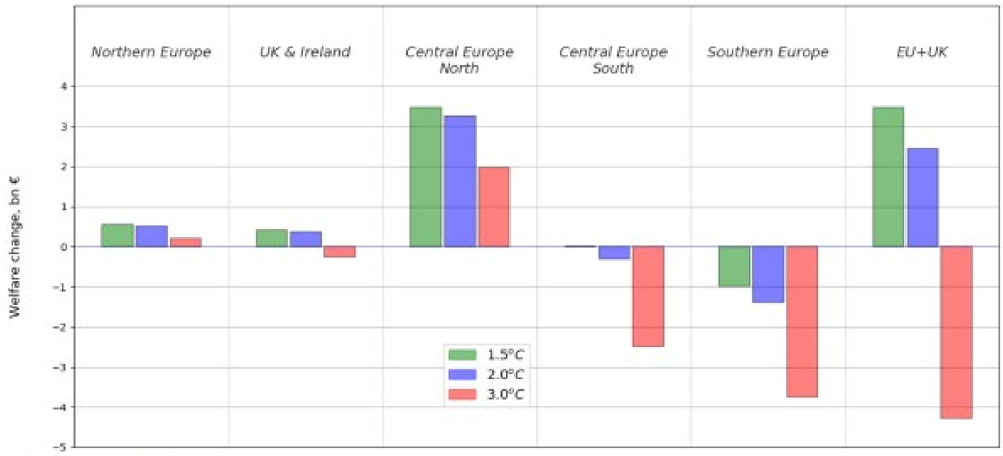
The combination of climate model, impact model (crop model or statistical), and economic model (partial equilibrium or CGE) lead to an enormous range of uncertainty, and this is compounded by the continued debate on the positive role (or not) of CO_2 fertilisation, which can reduce yield impacts or even lead to net positive effects. These results can change further again when the consideration of reactive farm adaptation is considered. This means it is possible to find studies that cover the entire range from large negative to high positive outcomes for the UK. This study has reviewed some of the economic literature, focusing on studies that take account of international effects.

The PESETA study (Ciscar et al. 2012) used crop model outputs in a CGE model and estimated the impacts of climate change on agriculture in Europe. They estimated it would reduce GDP by 0.3% overall, but with strong distributional patterns, with small productivity and economic gains observed in the Northern European regions (including the UK) but large losses observed in Central and Southern Europe. The PESETA II study (Ciscar et al. 2014[lxxv]) built upon this work and reported losses in monetary terms. It estimated climate related costs for agriculture of €18 billion/year in Europe by the 2080s (A1B), driven by yield reductions in Southern Europe. When a warmer and drier climate was considered, with no adaptation, the UK and Ireland were projected to experience yield losses in the range of -10 to -20%, but these could be offset completely with adaptation. The most recent PESETA IV (2020[lxxvi], [lxxvii]) study again reported that in the absence of adaptation, climate change could substantially lower grain maize and wheat yields in southern Europe, and to a lesser extent grain maize yields in northern Europe (although there were projected gains in the UK). However, economic modelling found that production in the EU and UK could still increase slightly due to the interplay of different market forces, i.e. because the negative effects in Europe are projected to be lower compared to other world regions. This provides the EU a comparative advantage in terms of climate change impacts on agricultural productivity, which could positively affect its competitiveness. Interestingly it finds a tipping point for the UK above 2C, when there is a flip to a decrease in yields, and for welfare.

Table 8 Change in welfare (bn €) from crop productivity change for the EU regions for the three climate scenarios. The reported changes are with respect to current economy Source PESETA IV, 2020.

Region	Welfare (bn €)			Welfare (% of GDP)		
	1.5°C	2°C	3°C	1.5°C	2°C	3°C
Northern Europe	0.6	0.5	0.2	0.06	0.06	0.02
UK & Ireland	0.4	0.4	-0.3	0.02	0.02	-0.01
Central Europe North	3.5	3.3	2.0	0.09	0.08	0.05
Central Europe South	0.0	-0.3	-2.5	0.00	-0.01	-0.09
Southern Europe	-1.0	-1.4	-3.7	-0.03	-0.04	-0.12
EU + UK	3.5	2.5	-4.3	0.03	0.02	-0.03

Source: PESETA IV, 2020.



Source: PESETA IV, 2020.

Balkovic et al. (2015[lxxviii]) estimated the difference in welfare (the sum of producer and consumer surplus) with and without climate-induced yield shocks using the partial-equilibrium model GLOBIOM for a 2°C scenario (mid-century). They found that when adaptation was included, climate change had an overall positive monetary aggregated impact on land-use related sectors in Europe of USD +0.56 billion/year, but found a loss of USD 1.96 to 6.95 billion/year without adaptation including losses in the UK. They identified large uncertainties, partly due to the estimation on yield impacts, and the damage estimation was directly related to the production losses estimated using crop models, which in turn was directly dependent on assumptions on rainfall and precipitation patterns estimated using climate models.

The COACCH project (2020[lxxix]) used crop models inputs and used in the GLOBIOM model, to estimate the impact of climate change on EU-28 production, area, and yield, looking at individual crops and broad agricultural categories. In all scenarios (low, medium and high warming scenarios), when CO_2 fertilization was included, crop productivity was projected to increase on average in Europe, but there were large differences between crop types, as well as spatial differences within Europe.

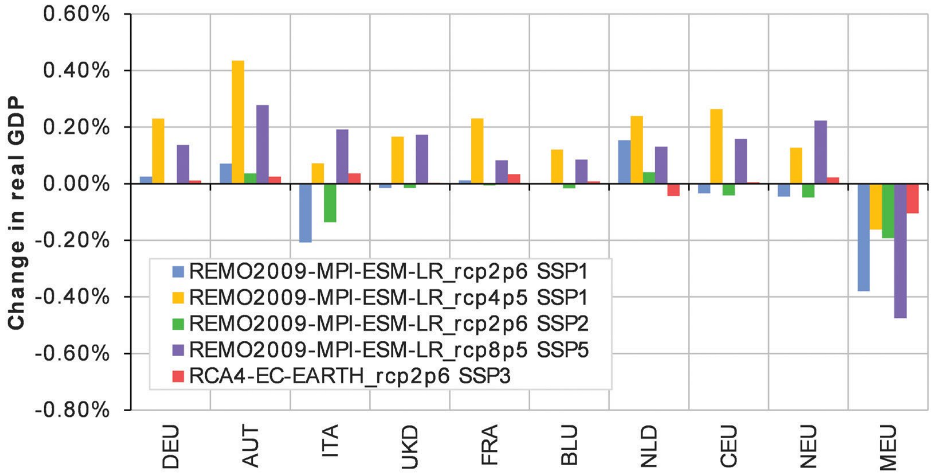


Figure 6 Changes in real GDP in 2050 due to the combined effect of changed cropland availability and yield changes, relative to a Baseline scenario without climate change.

(DEU: Germany; AUT: Austria; ITA: Italy; UKD: United Kingdom; FRA: France; BLU: Belgium and Luxemburg; NLD: Netherlands; CEU: Central Europe; NEU: Northern Europe; MEU: Mediterranean and South-Eastern Europe).

The Highest negative impacts on both crop yields and the agricultural sector in general, were found under a high emission scenario (RCP8.5) when CO_2 fertilisation was not considered. GLOBIOM estimated that under this scenario, the production costs of climate change are in the order of 906 million Euros for arable production and 831 million Euros for the agricultural sector in 2050. For the UK, the largest changes constituted a positive effect of around 0.18%of GDP in 2050 under RCP4.5 – SSP1 and RCP8.5 – SSP5 scenario combinations. Negative effects were found under RCP2.6 – SSP1 and RCP2.6 – SSP2 combinations though they were almost negligible. These estimates consider the fact that the negative impacts of climate change are more profound in the rest of the world compared to Europe, leading to a relative improvement in Europe's export position, but also increasing pressure on European resources such as land and water.

There is less information on the effects of livestock. There are some studies that review the potential effects in the UK (Wreford et al., 2020[lxxx]), though there is less information on the potential quantified impacts.

Analysis by Fodor et al. (2018) using the UKCP09 11-member PPE indicated possible average annual milk production losses from the THI relationship, but with considerable interannual variability, with the hotter locations projected to show an annual milk loss exceeding 1,300 kg/cow by the 2090s (ca. 17% of today's productive capacity). In order to address some of the key uncertainties, this study also developed an improved model and concluded that SW England is the region most vulnerable to climate change economically because of the combination of high heat stress with high dairy herd density such that income loss for this region by the end of this century may reach £13.4m in average years and £33.8m in extreme years.

One recent study analysed the implications of heat stress in dairy cattle and in turn milk production using the temperature-based component of the established thermal humidity index (Jones et al.

(2020). The study assessed the spatial variation of threshold exceedance across the UK, and assessed climate impacts using the CMIP5 climate projections, for present day the 2050s and the 2080s. Exceedance of the air temperature threshold was found to lead to a decline in milk production and decreased conception rates. In terms of milk production, the analysis found a steep increase in total milk losses after the 2050s. At the UK level, the estimated economic impact range from £3 million to £4.5 million per annum, depending on current climate variability. Costs increase to between £8 million to £13 million by 2050s, and to between £17 million and £57 million in the 2080s.

In England, economic impacts range from £13 million to £45 million per annum in the 2080s. The larger share of costs in England reflects the fact that 60% of cows are currently reared there and threshold temperature exceedances tend to occur more frequently in England compared with other regions. Economic impacts in Scotland, Wales and Northern Ireland ranged from £0m to £7m per annum in the 2080s depending on the model. The magnitude of these impacts compared to current UK value of milk production implies that by 2080s total milk losses would range from around 0.4% of total production to 1.3%. Current profit margins are 6% on milk yield, suggesting that future losses could be significant. The regions most impacted include south west England, north west England, the west Midlands, Wales and Northern Ireland.

Forestry

Forestry is a sector with long lifetimes, and thus high risk from climate change. As with agriculture, forest growth may be positively impacted by some climate change effects but negatively impacted by others, with the latter including changes in water availability, extremes (droughts, wind storms) and pests and diseases. Additional impacts can arise from changes in forest ecosystem health, and from increasing forest fires, affecting managed and natural forests.

Climate change affects the forest sector in two ways; first, through the impact on biomass accumulation and the growth rates on forests, and second, through the enhanced risk of forest fires.

Hanewinkel et al. (2013)[lxxxi] estimated the economic impact of projected climate change for a wide range of temperature increases (between 1.4 and 5.8°C until 2100), using a high-resolution model that predicted presence or absence for 32 tree species under different climate projections (A1B, B2 and A1F1) in Europe. They found that the expected value of European forestland will decrease owing to the decline of economically valuable species in the absence of effective counter-measures. Depending on the interest rate and climate scenario applied, this loss varies between 14 and 50% (mean: 28% for an interest rate of 2%) of the present value of forestland in Europe, excluding Russia, and may total several hundred billion Euros.

The COACCH project (2020[lxxxii]) looked at productivity and fires using the biophysical forest model G4M. This estimated that increased temperature and decreased precipitation cause a reduction in the biomass and growth rate of forests in Southern Europe, especially towards 2070 under RCP8.5. In the short-term, smaller gains on biomass growth were projected in Northern Europe. Under RCP8.5 and without CO_2 fertilization, it estimated that the costs of climate change for forest production, related to the loss of biomass, amounted to 62 million Euros in 2050 and 112 million Euros in 2070 for Europe. In the UK the climate change costs were estimated to be negligible, though forestry in the East of England was judged to lose productivity whilst it increases in Scotland.

Studies on forest fires project an increase in frequency and extent, especially in Southern Europe. Fires currently affect more than half a million hectares of forest each year, with estimated economic damages of €1.5 billion annually (San-Miguel-Ayanz and Camia, 2010): studies estimate the area burned in Europe could increase by 200% by the 2080s due to climate change (Khabarov et al. 2016) – although this excluded the UK.

The COACCH project (2020) estimated that the potential burned area in Europe will increase significantly in Europe, especially under the RCP8.5 scenario. The areas (in ha) are estimated to be largest in Portugal, Spain, South of France and Greece. Given that the losses in the UK are likely to be relatively small compared to these countries, it considered that there is therefore the potential for timber demand to be switched so that it is met by UK production with higher prices resulting in higher profitability.

The PESETA II project (Ciscar et al., 2014) estimated that burned area due to forest fires could more than double in the Southern European region in the reference simulation, reaching almost 800,000 ha. The PESETA IV study (Forziere et al., 2020[lxxxiii]) undertook a detailed current study of climate risks and considered damage from fires, windstorms and insect outbreaks is likely to increase further in coming decades, and Costa et al., (2020[lxxxiv]) looked at wildfires across Europe by country, and projects increasing fires for the UK but did not monetise these.

Valuation summary

Estimation is complicated by the fact that the opportunities resulting primarily from changes in the mean climate need to be balanced against the risks from extreme weather events. Thus, substantial local or regional changes may be balanced out at the national scale. There is also an extremely large range of results across the climate model projections, and according to assumptions about CO_2 fertilisation. Values are presented separately for agriculture and forestry. There is insufficient information to provide a breakdown by country, but it is noted that the forestry sector is particularly important for Scotland.

Agriculture

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	High	Range from High positive to High negative	Range from High positive to High negative	Range from High positive to High negative	Range from Very High positive to Very High negative	Very high
Confidence		Low	Low	Low	Low	

Forestry

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK		Range from low to high	Range from low to high	Range from low to high	Range from low to very high	Not known
Confidence		Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation

There are a number of studies on costs and benefits of adaptation actions (Watkiss and Hunt, 2018[lxxxv]), although their conclusions depend on the modelling approach (i.e. whether using farm level analysis, crop models, econometric analysis, or partial or general equilibrium models). Early studies using crop productivity models tend to identify increased use of irrigation and fertiliser to address changing yields, but rarely covered potential limits (e.g. water availability or implications of fertiliser use). Another series of models use partial or general equilibrium models to analysis adaptation options including trade, shifting crop types and land-use expansion. These highlight important issues of market driven adaptation, and that changes that occur from impacts in the UK need to be seen in the European and even global context. Such studies (e.g. Hristov et al., 2020[lxxxvi]) report that large negative climate change impacts on productivity outside of the EU can lead to large market spill-over effects which could push up production in Northern Europe (including the UK, and assuming production capacity is available) as higher demand for some agricultural commodities outside of EU results in higher producer prices.

At local level, economic studies have found a large number of no- and low-regret options including agronomic options such as changing sowing dates, planting new cultivars or varieties, or changing management practices (Watkiss and Hunt, 2018). These are often already implemented as reactive or even planned measures by farmers as adjustments to weather and climate variability, however effectiveness is usually highly variable depending on the context for the measure, and differs for crops and regions. As discussed in previous CCRAs, more strategic options that have good benefit to cost ratios include increasing water supply through on-farm storage reservoirs and incentivising efficient water management, the introduction and increasing expenditures on research and development (Wreford and Renwick, 2012[lxxxvii]: Moran et al., 2013[lxxxviii]; Frontier Economics, 2013[lxxxix]). In addition, studies also support early options that focus on enhancing adaptive capacity through research, awareness, information provision, best practice and addressing barriers. This may be complemented by further investment in weather and climate services (seasonal forecasting etc.) to improve the quality of information on climate sensitivity and further support for technological developments, notably precision agriculture.

In particular, and highlighting the risks transferred from the land use sector to biodiversity, soils and water (see Risks N1, N4, N11), there is enhanced policy interest in ‘climate-smart’ initiatives, although here additional policy support will likely be crucial, as through agri-environment scheme payments. For agriculture, direct benefits from improved environmental protection for farm incomes (rather than society as a whole) generally take longer to accrue, and include non-market and off-site benefits. For individual practices, benefit to cost ratios are often highly site-specific, with varied evidence on practices as viable standalone adaptation strategies (e.g. Kuhlman et al.,2010[xc]). Previous qualitative economic appraisal by Frontier Economics (2013) found UK farming uptake of soil protection measures was relatively low, partly influenced by awareness but also financial return.

A report commissioned by the CCC from JBA Consulting (CCC, 2018[xci]) examined how taking a long-term approach to considering the risks from climate change, and anticipating land-use changes to manage these risks, could deliver net benefits in terms of the maintenance of natural capital and the services it provides. An 'adaptation pathways' approach was used to develop understanding of how the need for planned transformational change can be understood and analysed. Four case study locations were scoped for the research all of which had agriculture as a significant proportion of existing land use: Norfolk and Suffolk Broads; Somerset; the Petteril; and Moor House and Upper Teesdale. The case studies showed that in scenarios where future climate change presents a threat to current land uses, the use of adaptation pathways that consider land-use change in advance of the climate hazard event occurring deliver higher net benefits compared to waiting until the hazard has occurred. Anticipatory action was shown to improve total net benefits over and above a business as usual scenario by between £2,500 per ha and £8,400 per ha across the four English case study locations analysed in report.

Posthumus et al. (2015[xcii]), using an ecosystem services valuation approach, found that for soil erosion, use of tramline management, mulching, buffer strips, high-density planting and sediment traps were the most cost-effective control measures, with contour ploughing also cost-effective in some circumstances. However, as above, the study also found that assessments of effectiveness really need to be made at farm level or field level, because of the wide variation in biophysical and land use contexts, emphasising again the key role of outreach and guidance in stimulating proactive adaptation actions on the ground. SRUC (2013[xciii]) for the CCC also looked at soil management, considering six adaptations on a number of different crops. Under these assumptions, all the adaptations analysed (with one exception, for cover crops) generated positive NPVs. These did not require long lead times and had positive ancillary benefits, but the study still identified the challenge would be to encourage farmers to adopt them. All of this suggests that while sustainable soil management approaches have potential for reducing climate impacts, their uptake requires these barriers to be addressed, and may need a combination of awareness and incentives to realise

(Watkiss et al., 2019) though there are obvious opportunities to provide additional incentives through revision of the current farm payment schemes.

Livestock adaptation options have been evaluated by Dittrich et al. (2017[xciv]). The costs involved in adapting the farming system range from simple low- or no-cost to those requiring large investments of capital and labour (Wreford et al., 2015[xcv]; Wreford and Topp, 2020[xcvi]). The lead-time and lifetime of that adaptation measure influence the choice of economic appraisal method used for the evaluation (Dittrich et al., 2017). In the case of short-term decisions that require a small investment or a reversible cost-benefit analysis (CBA) is appropriate. On the other hand, projects that have a longer lead-time or long lifetimes require methods that incorporate uncertainty (Dittrich et al., 2017). Thus, when farmers consider changing the composition of the dairy herd to maximise productivity and minimise stress, portfolio analysis, which evaluates several options in terms of herd structure, is appropriate. However, when the impact on the farmer relates to the frequency of extreme events, real option appraisal can be used as it allows for learning over time, and this method may be more suited to natural flood risk management measures to protect livestock and agricultural land, and housing to protect animals from heat.

Studies on adaptation costs and benefits in relation to sustainable forestry management investigate the challenges in making long-term decisions over individual or multiple rotation cycles. Increasingly these show the advantages from moving to a more diversified system rather than monocultures as developed in the past, as also consistent also with the general shift towards multifunctional forestry, including the increasing present and future threats from pests, pathogens and INNS (Risk N8) (e.g. Ray et al., 2019[xcvii]).

N7 Risks to agriculture from pests, pathogens and invasive species

CCRA3 findings

Chapter 3 of the CCRA summarised the evidence on this risk. This involves a large number of possible plant and animal diseases. Pests, pathogens and invasive non-native species present serious risks to agricultural productivity, with consequences for livelihoods and businesses. The combined risk factors (climate and non-climate) clearly suggest that the magnitude of this risk is increasing. The CCRA3 Technical Report identified a number of potential threats. In general terms, the trend towards warmer and seasonally wetter conditions, most especially in winter months, was considered very likely to favour increased risk from some existing pests and pathogens. In assessing risk from INNS, distinctions between introduction and establishment as compared to spread and consequent impact become important as the magnitude of impact increases at each step.

Valuation

The valuation analysis has focused on case studies to explore this risk. The UK Biological Security Strategy (The Home Office, 2018), reports that between August 2000 and December 2017 there were 22 outbreaks of exotic notifiable animal diseases in the UK that cost the Government between £300,000 and £3 billion. The Environmental Audit Committee (2019) report on Invasive Species identified INNS as one of the top five threats to the UK's natural environment. Previously, and reported estimated total costs to the GB economy of £1.9 billion per year (£1.5 billion to England, £0.26 billion to Scotland and £0.15 billion to Wales.

Yellow Rust and Septoria on Winter Wheat

HGCA (2012[1]) state that yield losses of 30-50% in winter wheat production have been reported and susceptible varieties can average a yield loss of 20% in untreated trials. Watkiss et al. (2019[xcviii]) estimate that there is a loss equivalent to a cost of £250 per hectare, based on a grain price of £150/tonne and an average treated yield of 8.5 ton/hectare. Adopting a figure of 15 million tonnes for total winter wheat production in England, (Cho et al. (2012[1])), and assuming the yield loss of 20%, this gives rise to a total current annual cost of £450 million. Under climate change, Gouache et al. (2013[xcix]) project that *septoria tritici* incidence could be reduced by 2-6% at three sites across France by 2071-2100. Transferring this impact estimate to England, Watkiss et al. (2019) project this cost to be reduced by £9m - £27m per annum.

Bluetongue virus (Culicoides)
Bluetongue is a viral disease of cattle and sheep transmitted by *Culicoides* biting midges; there have been a number of recent outbreaks of the disease across Europe, including England and Wales. Jones et al. (2019[c]) identify that the risk of disease outbreaks are likely to increase under climate change futures as a result of a number of factors including population size, mortality rate, the virus replication rate and biting rate that are all temperature-dependent. The authors undertake modelling of farm infection rates under two climate change scenarios – RCP4.5 and RCP8.5. They report that outbreaks are approximately double the current number of 440 farms infected by the 2050s - 760 and 850 farms for RCP 4.5 and 8.5, respectively, and a further slight increase for RCP 4.5 to 900 by the 2080s, with a more significant increase to 1,250 farms for RCP 8.5 by the 2080s.

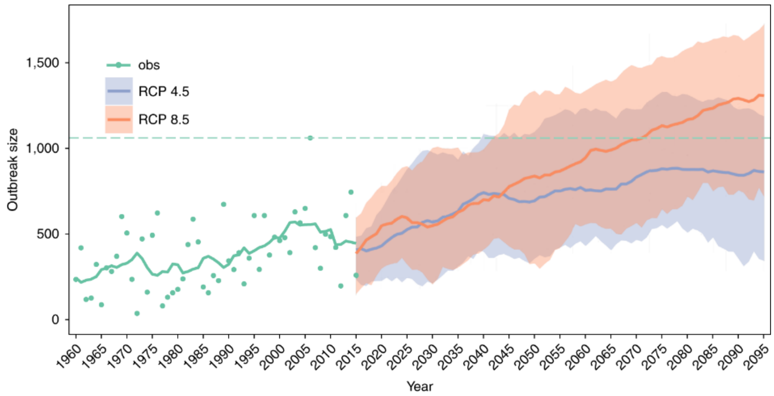


Figure 7 Average (median) simulated BTV outbreak size in England and Wales under future climate

We use the results from Jones et al. (2020) to generate indicative estimates of the costs associated with BTV under climate change scenarios. Unit costs for cattle are identified in Gethmann et al. (2020)[ci]. They estimate the direct costs which include production losses, animal deaths, and veterinary treatment as well as the indirect costs which include surveillance, additional measures for animal export, disease control (preventive vaccination and treatment with insecticides), vector monitoring, and administration. The financial impact of a BTV-8 infection at the animal level was estimated to average £130 per dairy cattle, £30 per beef cattle, and £75 per sheep. The cost of the epidemic as a whole was estimated to be £180 million for Germany. Only 27% of the total cost comprised of direct costs, with the remaining 73% being indirect costs. Studies in other countries show widely differing results depending on the assumptions made in the methodological approach. Nevertheless, the example of Germany – with a cattle and sheep sector of a size broadly similar to that in the UK – provides an initial indication of the possible dimension of this risk. If we assume that all cattle on affected farms are affected by the disease, and we utilise the figure for the average number of cattle on a farm in the UK as £130, then the cost totals can be calculated, as presented in Table 1. The frequency with which outbreaks occur are also projected to increase from the current 1 in 20 years (Jones et al.). The frequencies are projected to be 6 in every 20 by the 2050s for both emission scenarios and the 2080s for RCP4.5, and around 13 years in 20 by the 2080s for RCP 8.5. The resulting annual average costs are also included.

Table 9 Cost of BTV Outbreaks under Climate Scenarios – England & Wales

Time period	Climate Scenario	Total cost of outbreak (£m)	Total Climate-related cost (£m)	Annual Climate-related cost (£m)
Current	Baseline	7.2		
2050	RCP4.5	12.4	5.2	1.6
	RCP8.5	13.9	6.7	2.0
2080	RCP4.5	14.7	7.5	2.2
	RCP8.5	20.4	13.2	8.6

Phythophthora infestans
The risk assessment suggests that greater frequency of warm, dry, summers under climate change could increase the likelihood of the pathogen, Phythophthora infestans, causing late potato blight – the disease that resulted in the Irish Potato famine in the 19th century. The current size of this risk is indicated by the findings of Haverkort et al. (2008) who estimate that the annual costs of potato blight in the EU are around Euro 1 billion, equivalent to 15% of the total value of potato production. These costs comprise of existing disease control costs as well as the value of lost output. Assuming that the 15% estimate applies to the UK, an average annual total production value of £515 million (AHDB, 2020) implies an annual loss of £77 million. This can be disaggregated to £18 million for Scotland, £6 million for Wales, £1.5 million for Northern Ireland and £52 million for England. However, there is not good information on how much these costs would increase under future climate change scenarios.

Tobacco Whitefly (Bemisia tabaci)
Whitefly is considered to be one of the most serious threats to crop cultivation worldwide. In regions where it is established, viruses transmitted by this insect, especially those affecting tomato and cucurbits, and also beans, pepper and aubergines, are responsible for severe diseases that have a strong negative impact on crop yield (EFSA, (2013[cii])). Indeed, it has been estimated that a whitefly outbreak in the United States resulted in £375 million worth of damage in a single year (Oliveira, et al. 2001[ciii]). Bradshaw et al. (2019[civ]) identify this as an agricultural pest that has the ability to transmit multiple damaging plant viruses. To date, UK outbreaks of the whitefly have been restricted to glasshouses and there are no records of the whitefly establishing outdoors during the summer. However, they project that under 2°C and 4°C climate change scenarios the pest could pose a risk to outdoor UK crops in July and August. Specifically, they find that *B. tabaci* could establish outdoors in East Anglia and across southern England in the future. However, no quantification is given of the likelihood and size of this risk and its impact on agricultural production.

Haemonchus contortus
An additional risk that has been quantified in the study by Jones et al. (2020)[cv] is the influence of higher temperatures on incidences of the sheep parasite *Haemonchus contortus*, and the implications for lamb production. The study extracted data from UKCP18 12 km projections for a RCP8.5 concentrations pathway. A single ensemble member was selected, roughly mid-range of the set of ensembles. The research suggests an increase in the number of days where daily mean temperature exceeds a temperature threshold of 9 °C, which allows sheep parasites to increase their life cycle more frequently, with health impacts for sheep and economic costs to farmers.

For the UK as a whole, at the baseline annual economic losses are already £81 m per year (see Table below). This compares to the total production value of sheep meat in 2018 at £1.2 billion in the UK, around 7% of total production[1]. Under the 2°C scenario, monetary losses increase to £97 m per year while under the 4°C scenario they total £113 m per year. In England, losses increase from £37 m per year at baseline to £43 million and £50 million per year under 2°C and 4°C scenarios respectively. In Wales they increase from £22 million per year to £27 million and £31 million per year, while in Scotland annual losses increase from £16 million to £20 million and £23 million. In Northern Ireland they increase from £4.8 million to £6.1 million and £6.7 million per year. Projected economic costs of greater parasitic outbreak could thus cost up to 10% of the value of lamb production under a 4°C scenario.

Table 10 Annual economic losses in lamb production by region. Average over a ten year period for baseline (2001 – 2010), 2°C and 4°C scenarios.

		Monetary loss (£ million)		
Region	**Total no. lambs (million)**	**Baseline (2001-2010)**	**2 °C**	**4 °C**
England (total)	8.0	37.6	43.8	51.0
Northern Ireland (total)	1.0	4.9	6.1	6.7
Wales (total)	4.9	23.0	27.4	31.8
Scotland (total)	3.4	16.0	20.1	23.7
UK (total)	**17.3**	**81.4**	**97.4**	**113.2**

Asian Hornet
Asian hornets have been identified as currently living in the UK. For example, Defra reports that a nest was identified and destroyed in Gosport, Hampshire in September, 2020. The identified risk is primarily to honey-producing bees in the UK. An estimate of the economic value of bees in the UK was made by Carreck and Williams (1998[cvi]) and included both the value of honey produced, and the value of flower pollination. The study found a total value of approximately £250 million. No quantification of the potential risk from the Asian Hornet has been made to date. However, if we use a hypothetical "what if" scenario that assumes a reduction of 5-10% in bee productivity as a result of Asian Hornet attack, the loss in economic value of £12.5 million to £25 million would result.

Valuation summary
Changes in the climate can affect the suitability and geographical range for pests and diseases and may also, in combination with changes in extremes, affect the prevalence and intensity of pest and disease outbreaks. The economic costs of these outbreaks can be very high, once established. However, making precise projections of the changes in specific pathogens, and the subsequent impact, is much harder. We therefore consider that a conservative rating would suggest a Medium valuation to the 2050s and a High estimate under scenarios for the 2080s.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Medium	Medium	Medium	High	High	Not known
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation
Consistent with the discussion above, the economic case for further uptake of existing adaptation measures is sound, as evidenced by case study analysis on pests and pathogens (Watkiss et al., 2019): it is much more effective to prevent introduction and establishment rather than attempt to mitigate spread and resulting impacts. However, this additional uptake of measures has an associated resource cost. There is a clear a role for public co-ordination of monitoring and surveillance. Previous analysis by SRUC (2013) has identified that investment in monitoring for pests has a high benefit-cost ratio of around 10:1. The Environmental Audit Committee (2019) identified that expenditure on GB biosecurity is ca. £220 million per year, but invasive species only receive 0.4% of that sum (£0.9m). There are also clear benefits from Government investing in information about pests and pathogens – their spread, likely impacts, and treatment methods – as this information flow would not otherwise occur. Whilst a large proportion of the costs (for pests and pathogens) may be borne by private land-owners, public support is likely to be needed where there are local concentrations of economic activity that are threatened by the rapid spread of one of these pathogens in an area (to reduce the much larger costs once pests and pathogens become established). This economic argument is strengthened by climate change, because the future nature of threats will in many cases be distant from private actors' past experience.

N8 Risks to forestry from pests, pathogens and invasive species

CCRA3 findings
Chapter 3 of the CCRA Technical Report summarised the evidence on this risk. Pests, pathogens and invasive non-native species present serious risks to forest productivity, with consequences for livelihoods and businesses, and for the multiple ecosystem services that forests provide. The combined effect of risk factors (climate and non-climate) indicates that the magnitude of this risk is increasing. The relationship of this risk with climate change is complex. Each problem species or

micro-organism has its own specific climate sensitivities that can favour their increased incidence. In addition, socioeconomic factors are highly influential, both management factors at forest/stand level and large-scale drivers such as trends towards globalisation of trade and travel.

A number of specific risks were identified in the CCRA3 assessment. These include:

- Dothistroma needle blight of pine, which causes premature needle defoliation and reduces timber yield (and in severe cases causes tree mortality);
- Phytophthora ramorum, which affects trees and other plants, although the disease is a particular problem for in the UK for larch grown for timber;
- Thaumetopoea processionea (Oak processionary moth);
- Ips typographus (large eight-toothed European spruce bark beetle);
- Dondroctonus micans (great spruce bark beetle);
- Elatobium abietinum (green spruce aphid).

<u>Valuation</u>
The valuation analysis has focused on a number of case studies on specific risks, to explore the potential magnitude.

Dothistroma (Red band) needle blight (DNB)
CCRA1 assessed the potential monetary impact of Red Band Needle Blight. This used analysis from the Forestry Commission (2010) and values from Chiabai et al. (2009), for the marginal values for forest ecosystem services for cold coniferous forests, with a marginal value of the ecosystem services provided by forestry of approximately £334 per hectare. For the central estimates, the damage costs ranged from zero to £2 million in the 2020s and up to £12 million by the 2080s. More recent studies also project impacts. Red band needle blight is projected to increase to 2050 as a result of the higher projected winter rainfall (Ray et al., 2017[1]). The Forestry Commission (2012) judges that there is a risk of a significant reduction in Great Britain's forest resource due to this disease – particularly Scots pine, Lodge-pole pine and Corsican pine. We use the results of the Ray et al. (2017) study that estimated changes in pine timber production under a climate change scenario as a result of DNB. This projects approximately a 2m^3/ha (0.7%) annual loss in pine trees to 2050. Since there are approximately 320,000 hectares of coniferous production in England – equivalent to 87 million cubic metres – this rate of loss would lead to a total of 211,400 hectares by 2050. At £29.02/m^3, the current market price for coniferous wood, which we estimate equates to a total, discounted cost of £300 million.

Phytophthora ramorum
Phytophthora ramorum generally favours warmer and wetter conditions over autumn/winter/spring: it might therefore become more prevalent (Sturrock et al., 2011[1]), as these conditions are projected by UKCP18. The primary cost of *Phytophthora ramorum* is the loss of revenue resulting from the decline in larch wood production and sales. The cost of managing and slowing the spread of *Phytophthora ramorum* in the UK was reported at £23 million between 2009 and 2014 (Defra, 2018[1]). Based on its average height, we assume that the average mature larch tree produces the equivalent of 20 cubic metres of wood. The current price of coniferous wood per cubic metre is £29.02 (2016 constant prices).[1] On average, over the last eight years, the annual average volume of infected wood – estimated from data on the stands being given SPHNs – is estimated to be 77,500 cubic metres. There is no evidence that these recent infections have been associated with climate change; the reason for the spread of the disease from California to Europe fifteen years ago and its subsequent spread around Western Europe is not known. If, however, it was assumed that a change in climatic conditions had facilitated this spread so that all this recent loss was attributed to climate change, the current annual cost would be £2,250,000.

This cost, in future years, will be affected by the patterns of pathogen spread and the stock of living larch trees across the country. Given that England is expected to experience more warm days of 18-22°C under all climate change scenarios, and that wetter winters are also expected, climate change could enhance the spread of the pathogen (although this might be somewhat reduced by drier summers). In the absence of detailed evidence, a “what if” scenario assumes that the current annual average cost continues to be borne until 2050. This may be plausible given that - combined with the fact that climate change is projected to result in growing conditions more conducive to larch[1] - the pathogen is likely to be more challenging to manage under a changing climate. The total cost would then be £67,500,000. However, this value may be judged to be somewhat of an upper bound estimate as infected wood can still be sold at the market price, and the trees that are felled can – after a fallow period of three years - be replaced with alternative tree species that produce commercially valuable wood. It is also unlikely that current costs can solely be attributed to climate variability.

Thaumetopoea processionea (Oak processionary moth (OPM))
In response to a warming climate, OPM is expanding its range northwards, while outbreaks are increasing in frequency and intensity, particularly in northern Germany, the Netherlands, and southern UK, where it was either absent or rare previously (de Boer and Harvey, 2020). OPM caterpillars are capable of stripping foliage from their food plants (oak and pine trees), generating considerable economic damage as well as presenting a human health risk -infestations of *T. processionea* may lead to dermatitis, conjunctivitis, and pulmonary problems in humans due to the urticating hairs which in turn will require treatment and thus has associated medical costs. The hairs can also affect animals, which would have a negative impact on the livestock industry, either in treatment costs or the loss of livestock. Quantified projections are currently absent from the literature. Whilst it is reported that each case may cost £500 to manage, the lack of knowledge regarding transmission frequency means that there are no estimates of number of tree cases under alternative climate scenarios.

Ips typographus (large eight-toothed European spruce bark beetle)
The larger eight-toothed European spruce bark beetle is a destructive pest of spruce trees as well as some tree species in other conifer genera (Forest Research, (2020)). If left uncontrolled, the beetle could cause significant damage to the United Kingdom’s spruce-based forestry and timber industries. This is especially so where pathogenic fungi are present, because the beetles can spread them. Historically, only very occasional outbreaks are detected and currently it is believed to have been eradicated in the UK. Although higher temperatures under climate change futures are projected to increase the likelihood of this pest spreading from mainland Europe, no quantitative estimates have been made as to the magnitude of this risk.

Dondroctonus micans (great spruce bark beetle)
The great spruce bark beetle (Dendroctonus micans) is not native to the UK and has the potential to be a significant pest of spruce trees. However, evidence on which to quantify the current and future risk is absent.

Elatobium abietinum (green spruce aphid)
Williams et al. (2010) estimated the cost of green spruce aphid at £3.6 million for the UK annually based on an average spruce timber price of £42/m^3 and a 3% loss of yield. Dividing this by the area affected in the baseline risk presented in this report gives an estimated cost of £46.35 per hectare affected. This assumes a spruce area of 770,000 hectares in Great Britain (Forestry Commission, 2010). This provides the information to allow an order of magnitude scaling of the impacts. Using the previous literature (Williams et al., 2010), we estimate damages caused by an increase in green spruce aphid with climate change. Net costs of climate change are provisionally estimated to be between zero and £17 million annually depending on the scenario. These costs do not consider the potential for adaptation – e.g. in terms of planting different species or aphid control strategies.

Chalara fraxinea (ash dieback).
Ash trees - in woodlands of 0.5 hectares or more in size - cover 141,600 hectares in Great Britain (5.4% of the total woodland) and 110,400 hectares in England (9.2% of total woodland). In addition, there is a further 38,500 hectares of ash in Great Britain’s smaller sized woodland (less than 0.5 hectares) and 32,100 hectares in England. Defra (2013) identified a range of ecosystem services associated with Ash trees, including: timber, recreation, cultural heritage, aesthetic, climate and air quality regulation, and habitat provision for other flora/fauna. The annual value of the Ash population

in the UK was estimated to be £230 million (Defra, 2019[cvii]), of which £22 million is commercial value of wood; the contributions of other ecosystem services are not stated.

Goberville et al. (2016[cviii]) ran simulations of the productivity of both ash trees and *chalara fraxinea* and their interactions, at the European scale. They found that by 2050 the productivity of ash – taking account of *chalara fraxinea* – may vary by between -15% and +50% under RCP2.6 and 8.5 scenarios, respectively. This is a consequence of the fact that the higher mean temperatures encourage ash growth whilst the projected increased dryness of the summers, particularly in Southern Europe, would constrain fungal growth. The current costs of *chalara fraxinea* on the ash tree population can be estimated on the basis that the disease has been detected in 36% of the 10km squares in England and the UK whilst – as noted above - the total annual value of the Ash population in the UK is £230 million. In the absence of UK-specific modelling, we have used the anticipated spread of the disease across Europe (a 15% decrease to 50% increase) and applied this to the UK stock through to 2050. The annual costs are estimated to be in a range from £34.5 million to benefits of £115 million, and are similar in size to the aggregate estimates made by Hill et al. (2019)[cix], of £14.8 billion, summed and discounted over the next 100 years. The estimates of Goberville et al. are disaggregated by country below. Note that these values are estimated based on the assumption that the size of ash tree coverage is not diminished in preceding periods as a result of *chalara fraxinea*, and that the potential spatial growth of Ash is facilitated in practice by forest managers allowing Ash to establish in areas hitherto un-economic. However, if the current risk is not managed and growth facilitated the range of values would be much reduced.

Table 11 Changes in annual value of Ash woodland by 2050s (£m)

	RCP2.6	**RCP8.5**
England	(26.4)	88
N Ireland	(2.9)	9.7
Scotland	(3.6)	12.1
Wales	(1.6)	5.2
UK	(34.5)	115

Valuation summary
The case studies above show that economic costs of these outbreaks can be very high, once established. However, making projections of the changes in specific pathogens, and the subsequent overall impact, is much harder.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
England	Medium	Medium	Medium	Medium	High	
N. Ireland		Not known	Not known	Not known	Not known	
Scotland	Medium	Medium	Medium	Medium	High	
Wales		Not known	Not known	Not known	Not known	
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation
The economic case for further uptake of existing adaptation measures is sound, as evidenced by the discussion above: it is much more effective to prevent introduction and establishment rather than attempt to mitigate spread and resulting impacts. Watkiss et al (2019) explored the possible costs and benefits of adaptation for a number of forest pests and pathogens (once established). The analysis indicated that it is possible to manage changing pathogen risks, at least to some extent, using existing

adaptation options. However, there are large resource costs associated. There are therefore benefits from further adaptation that avoids these risks. This includes a key role for public co-ordination of monitoring and surveillance.

Previous analysis by SRUC (2013) has identified that investment in monitoring for pests has a high benefit-cost ratio of around 10:1. There are also clear benefits from Government investing in information about pests and pathogens – their spread, likely impacts, and treatment methods – as this information flow would not otherwise occur. Whilst a large proportion of the costs (for pests and pathogens) may be borne by private land-owners, public support is likely to be needed where there are local concentrations of economic activity that are threatened by the rapid spread of one of these pathogens in an area (to reduce the much larger costs once pests and pathogens become established), i.e. management plans and emergency response. This economic argument is strengthened by climate change, because the future nature of the threats will be less understood by private actors' past experience.

Cost-benefit analysis of enhanced measures to address INNS are also discussed in Risk N7.

N9 Opportunities for agricultural and forestry productivity from new/alternative species becoming suitable.

CCRA3 findings
Chapter 3 of the CCRA summarised the evidence on this risk. Future climate change, especially warming, will enhance climate suitability for new crops but, there is limited evidence available to assess the magnitude of potential opportunities. The risk assessment identifies a number of agricultural crops and timber sources that may become more viable to grow in the UK for subsequent sale. Examples of these that are currently being introduced include: chickpeas, quinoa, grapes, soya, lentils, peaches, tea, watermelons, truffles, eucalyptus and Douglas fir. Future climate scenarios might allow additional crops such as biofuels as well as timber such as cherry and walnut.

Valuation
While this risk focuses on new crops and varieties, it is highlighted that depending on the study, there could be significant benefits from climate change on current crops and varieties, especially given changes in Europe and globally.

The economic welfare change as a result of introducing new crops and timber sources can be approximated by estimating the change in profitability that would result from the change in crop or land use. Such an estimation is complicated by the fact that non-climate supply and demand conditions are also likely to change. Whilst economic modelling is possible and has been undertaken at the global level (Nelson et al. (2014), to date this has not been undertaken in the UK. However, given the current size of agricultural production in the UK, which generates £8.5 billion of gross value added (NFU, (2017))[cx] and given that the fraction of crop and forestry production that is likely to change is constrained by technological constraints as well as market conditions, we speculate that the magnitude may be in the Medium or High categories, everything else being equal.

There is a case study on the opportunities for English wine from Watkiss et al (2019[cxi]). This found that climate change could to improve the agro-climatic conditions and productivity of English wine. By 2040, climate change could mean that England has become an 'intermediate climate' wine area, with higher wine suitability than today. After 2040, there are likely to be different future wine climates in England depending on whether a 2 or 4°C pathway arises. This analysis looked at the potential additional production that could arise, on top of planned wine expansion targets (Wines of Great Britain has estimated that in 2040 annual production could reach 40 million bottles (WGB, 2016)).

The analysis assumed that climate change would leads to a 25% increase in production due to climate change above the 2040 target, which would be an additional 10 million bottles in the year 2040, and translate to additional revenues (considering a range reflecting average and high value bottles, as well as the range of increase) of between £80 million to £200 million (depending on the %

increase and the value of the wine produced). A 50% increase, which might arise on a 4°C pathway could generate double this. These production increase would occur gradually from current levels, with production increasing year by year on average (noting high annual production variability). The cumulative financial benefits (up to 2040) from climate change could therefore be very large, as well as the annual benefit in future years. There is also a further benefit if climate change impacts on wine growing areas in other countries negatively in Europe (as projected), creating increased export opportunities for England.

Valuation summary

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
England		+High	+High	+High	+Very high	
N. Ireland		Not known	Not known	Not known	Not known	
Scotland		Not known	Not known	Not known	Not known	
Wales		Not known	Not known	Not known	Not known	
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation

The analysis of the wine sector (Watkiss et al., 2019) found there were early low regret actions that could be introduced to increase the opportunity presented by a warming climate, as well as to reduce the risks associated with possible climate variability (particularly the risks to grape growth from cold snaps). The study also found a large number of no- or low-regret options from Europe for addressing climate variability that could be adopted in the UK (e.g. Neethling et al., 2016[cxii]). The research also undertook an initial analysis of the potential costs and benefits of additional early adaptation. This indicated that under a scenario where wine growers were able to realise the benefits of climate change due to better information, and at the same time introduce adaptation measures to address potential variability risks, there would be very large economic benefits. The consideration of similar opportunities is less well characterised, but similar activities should be included for further investigation.

N10 Risks to aquifers and agricultural land from sea level rise, saltwater intrusion

CCRA3 findings

Chapter 3 of the CCRA summarised the evidence on this risk. It reported that future risk to aquifers - related to sea saline intrusion - is expected to gradually increase with sea level rise and may be more pronounced during drought periods. In turn, this creates a risk of water resource contamination and a negative impact on land productivity, most particularly on agricultural production, although there are some potential risks for eastern and southern England where some aquifers provide public water supplies. However, while there are some older vulnerability studies, there is not good, up to date national information on this risk under climate change, though they are considered important for high ++ sea level rise scenarios. Regarding impacts on water quality, 13 failures to meet good ecological status under WFD were attributed to saline intrusion in England and Wales, and 12 in Scotland in 2014. However, these make up a very small proportion (<1%) of total failures. Similarly, the effects of water salinization on agricultural land currently remain localised, although detailed risk mapping at national scale is not presently available.

Valuation

The economic welfare effects of saltwater intrusion are likely to derive partly from the higher charges for water users that result from lower fresh-water availability and/or the costs of desalinisation.

Additionally, saltwater intrusion into soil in coastal areas may adversely impact upon agricultural output. It is very difficult to monetise these as there is insufficient evidence on the scale of the risk, though current costs seem to be low. There is also some indication that the risk could be important under low likelihood, high impact scenarios, i.e. from extreme sea level rise.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	Not known	Not known	Not known	Not known	High
Confidence	Very low	Very low	Very low	Very low	Very low	Very low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation
There are some studies which include the impacts (in economic terms) of climate change on saltwater intrusion (e.g. see Brown et al., 2011[cxiii]: Hinkel et al., 2014[cxiv]), but these tend to be aggregated alongside flood damages, and are low in comparison, and these studies do not assess the costs and benefits of adaptation for salt water intrusion. There are also some case studies, but these tend to focus on urban areas, where there are very high economic costs (from contamination) and thus very different benefit to cost ratio. There is therefore a low-regret action to investigate this impact further (i.e. the value of information relating to saltwater intrusion adaptation options for agricultural land), and a more iterative approach which includes monitoring is generally considered a low regret option. There are examples of adaptation options to prevent vulnerable aquifers from saline intrusion, including saltwater intrusion barriers and freshwater injection (Xianli et al., 2010[cxv]) and cost-benefit information exists for these measures from countries with greater saline intrusion problems. These generally show when aquifers are in use, measures have economic benefits when compared to subsequent water treatment restoration costs (after contamination occurs).

N11 Risks to freshwater species and habitats from changing climatic conditions and extreme events, including higher water temperatures, flooding, water scarcity and phenological shifts.

CCRA3 findings
Chapter 3 of the CCRA summarised the evidence on this risk. It identified risks from reduced water availability, and higher water temperatures, are projected to increase the degradation of freshwater habitats and compromise the viability of some freshwater species. Freshwater habitats are particularly vulnerable to reduced water availability in the face of climate change but are also highly sensitive to the direct and indirect effects of temperature as well. The direct effects include: changes in river macrophyte communities; eradication of resident species; expansion of opportunistic species; loss of water connectivity; nutrient flows resulting in eutrophication and growth of algal blooms; phenological shifts e.g. of salmon spawning; and potentially loss or reduction in recreational fishing.

Valuation
Freshwaters provide the UK with a wide array of socioeconomically important ecosystem services, including water supply (for drinking, agriculture, and industry), pollution removal, and recreational potential (e.g. fishing and tourism). The annual value of these services, to the UK, has been estimated at approximately £39.5bn (Office for National Statistics, 2017) though, since this estimate does not exhaustively include all relevant ecosystem services, it will represent an undervaluation.

A recent climate impact national analysis (Jones et al., 2020[cxvi]), assessed four potential risks at UK scale where the thresholds that these risks are subject to, could be identified and quantified: algal blooms in lakes, algal blooms in rivers, loss of habitat for sensitive fish species, and changes in the composition of lake plankton populations. Given currently available evidence, economic valuation of risk was possible only for algal blooms in lakes. The authors use the values derived originally by

Pretty et al. (2003)[cxvii] who consider ten types of use value for water bodies affected by eutrophication. These include: (i) reduced value of waterside dwellings; (ii) reduced value of water bodies for commercial uses; (iii) drinking water treatment costs (to remove algal toxins and algal decomposition products); (iv) drinking water treatment costs (to remove nitrogen); (v) cleanup costs of waterways (dredging, weed-cutting); (vi) reduced value of nonpolluted atmosphere (via greenhouse and acidifying gases); (vii) reduced recreational and amenity value of water bodies for water sports, angling, and general amenity; (viii) net economic losses for formal tourist industry; (ix) net economic losses for commercial aquaculture; and (x) health costs to humans, livestock, and pets. Non-use values comprise the damage caused to biota and ecosystem structure by nutrient enrichment.

Using the valuation data from Pretty et al. (2003), Jones et al. (2020) estimate the impact of higher temperatures on incidence of harmful algal blooms in UK lakes. The costs of this risk alone, based on a single UKCP18 model variation, were projected to increase from £173m in the baseline (2001-2010) to £295m under a 2°C scenario and £481m under a 4°C scenario. The same study, using 28 model variants/projections from across the two families of ensembles available from UKCP18 data (PPE and CMIP5) on the trajectory towards a 4 °C world under a RCP8.5 concentrations pathway found that the figures were £264m and £332.3m respectively for the 2050s and £420m and £332m for the 2080s. The economic impacts in Scotland, Wales and Northern Ireland were much lower and range from £7m to £25m in the 2080s. Most of these costs occur in England for three reasons: it has more waterbodies susceptible, the incidence of temperature threshold exceedance is greater, and the economic costs are concentrated in more built-up regions in England. In addition to the economic cost reported here, increased frequency and severity of algal blooms could affect the ecological status of water bodies – rendering the investment that goes into maintaining good status obsolete. Such indirect costs are not included, but should be considered to avoid the inefficient position of spending more and more to meet a given objective in the face of increasing climate change risks.

Table 12 Economic impact of algal blooms in lakes due to exceedance of lake water temperature threshold (£ million), under RCP8.5 pathway, for baseline, 2050s and 2080s.

	CMIP5 (£ million)			**PPE (£ million)**		
Region	**Baseline (1990-99)**	**2050s (2040-59)**	**2080s (2070-89)**	**Baseline (1990-99)**	**2050s (2040-59)**	**2080s (2070-89)**
England total	157.8	235.0	291.9	162.6	291.0	364.4
Northern Ireland total	2.5	5.1	7.3	2.1	7.4	10.4
Wales total	8.2	12.4	16.0	6.5	15.4	19.7
Scotland total	4.9	11.3	17.1	2.1	15.3	25.9
UK total	**173.3**	**263.7**	**332.3**	**173.3**	**329.0**	**420.4**

Regarding studies of recreational fishing benefits, critical temperature thresholds have been determined for salmonid fish species which are important to commercial and sports fisheries. Whilst there has been no quantification of this potential impact it should be seen in the context of a sector which has substantial economic welfare value. A 2009 study indicated that the value of freshwater salmon fishing is equivalent to £350 million annually in England and Wales (Environment Agency, 2009[cxviii]). Any sizeable impact on these species from climate change would therefore be expected to be equivalent to a “High” negative valuation rating.

Valuation summary

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
England	High	High	High	High	High to Very high	Not known
N. Ireland	Low	Medium	Medium	Medium	High	
Scotland	Low	Medium	Medium	Medium	High	
Wales	Low	Medium	Medium	Medium	High	
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation
There is information in general on the costs and benefits of river basin management plans for England's water environment, as published in the Impact Assessment (Defra, 2015[cxix]), which include the options discussed in the section above, i.e. on possible options that might have high relevance for addressing increasing climate related risks. There is also some information published by the EA (2019[cxx]) as part of consultation, which highlights the need for an adaptive management approach to enhance the resilience of RBM plans. Similar information covering other parts of the UK has not been identified as yet.

N12 Risks to freshwater species and habitats from pests, pathogens and invasive species

CCRA3 findings
Chapter 3 of the CCRA summarised the evidence on this risk. Climate change is likely to affect pests, pathogens and invasive non-native species (INNS) through changed thermal regimes, with impacts on the distribution and spread of various diseases and INNS, the rate at which invaders competitively displace native species, or through their increased food consumption rates. Over 130 INNS are present in freshwater in the UK, with many of them being first reported in the Thames region. Climate variables, notably temperature, affect the potential distribution of selected INNS. However, other factors such as trade patterns and distance to ports are also important determinants. These effects are likely to result in a range of impacts including: competition with native species, introduction of disease, habitat alteration, among others. The analysis identified a number of potentially important INNS: these include crayfish but also pests and diseases that affect fish (including important recreational fish such as salmon).

Valuation
The potential economic welfare effects include the changes to recreational fishing opportunities, amenity value, water abstraction and use, and even increased flood risk from habitat alteration. Williams et al., (2010) suggest that the total cost for Great Britain could be £2.1 billion (2020 prices). In Great Britain, direct management costs for freshwater INNS have been estimated at £26 million per year (Oreska and Aldridge 2011), of which at least £4.6 million are borne by the water industry (Williams et al., 2010). As these figures are only direct costs, and do not include indirect damage to infrastructures and service losses resulting from infestations they are likely to be conservative. Indeed, UKWIR (2016)[cxxi] suggest that the sum of both direct and indirect effects to be borne by water companies is £7.5 million annually. Those for Northern Ireland have been estimated at over £46 million for all users (Kelly, 2013).

There appears to be no quantitative evidence of the impacts of freshwater pests and pathogens in the UK as a result of climate change. However, a study by Williams et al. (2010)[cxxii] estimates costs for the impacts of signal crayfish, introduced to the UK for commercial purposes, on the population of native, white-clawed crayfish. Williams identifies costs incurred in protecting the native crayfish population. For example, conservation and management costs for the native crayfish as around £500,000 per annum in England, £250,000 in Wales, and £190,000 in Scotland. Riverbank management costs are estimated to be £220,000 for England annually. Costs to anglers are estimated to be £600,000, £350,000 and £140,000 for England, Scotland and Wales, respectively, whilst research costs were £120,000, £42,000 and £41,000 for these three countries. Total annual costs of signal crayfish are therefore: England - £1.4 million; Wales - £0.43 million, and; Scotland - £0.58 million. The risk assessment notes that the signal crayfish has a higher upper temperature tolerance than the native species and so is more likely to survive under warmer climate change futures. However, no attribution of these costs currently and under future climate change scenarios is made. Williams et al. (2010) also estimates the costs of INNS on inland waterways more generally. These estimates included costs to angling, recreational boating and waterway management and totalled annually: England £42.5 million; Scotland £9.5 million; Wales £5 million. As with the estimates for crayfish, there is no attribution to climate change. However, modelling by Gallardo and Aldridge (2020)[cxxiii] suggests that minimum air temperature might be the most important of a range of environmental and socio-economic factors. Using what-if analysis to assume that the attribution to climate change is 10% in 2°C scenarios and 20% in 4°C scenarios we derive magnitude ratings as presented. We assume that since environmental conditions relevant to INNS in Northern Ireland are most similar to Scotland, ratings for Northern Ireland will follow those for Scotland.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	Low	Low	Low	Medium	Not known
Confidence	Very low	Very low	Very low	Very low	Very low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation

As highlighted above, once freshwater INNS become established, damage costs can be high, as can annual control costs. There is therefore an economic case for further uptake of existing adaptation measures to prevent introduction and establishment, rather than attempt to mitigate spread and address impacts. One issue is to know where to focus such efforts: Gallardo and Aldridge (2020[cxxiv]) undertook an example to prioritise risks (using cost-effectiveness for the prioritisation) identifying eleven invasive species that are most likely to cause disruption to the abstraction and distribution of water companies in the UK under climate change. There is also information in general on the costs and benefits of river basin management plans for England's water environment, as published in the Impact Assessment (Defra, 2015) and these include potential options for preventing the spread of invasive non-native species. These include biosecurity measures, monitoring, enforcing legislation banning or restricting the possession, sale and release, support for further research aimed at developing effective eradication methods and rapid response for early invasion. These actions are collectively shown to be economically efficient, i.e. benefits outweigh costs.

N13 Opportunities to freshwater species and habitats from new species colonisations

CCRA3 findings

CCRA identifies that opportunities for species and habitats may arise as a result of new species migrating to the UK from elsewhere, from expansion of the geographical range, and from higher local populations. This can include enhanced biodiversity, which supports a range of ecosystem services, particularly cultural ones such as recreation. For example, wetland birds have already migrated to – and started breeding in – the UK. For a range of climate change scenarios, wintering water birds are projected to continue to increase in number whilst other species are projected to decline in number. At the same time, damselflies and dragonflies, as well as a range of crustaceans are projected to move their ranges northwards, consistent with the warmer climate under climate change. Additionally, fish such as pike, perch and bream are projected to have increased population numbers.

Valuation

The potential changes have some potential benefits for ecosystem services. These could include enhanced recreational value. However, there is a lack of evidence on what these opportunities might be. For example, it is not known how patterns of freshwater fishing may be affected by potential changes in fish species and their availability, though if such changes occur, these could be significant. There is some information on charitable donations given to environmental causes (see N1 above), but there is no easy way to use this to get an estimate of potential valuation magnitude. Given this lack of evidence we cannot give an economic magnitude rating with any confidence, however, the main CCRA3 analysis indicates a low level, and this is reflected in the valuation analysis.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	+Low	+Low	+Low	+Low	+Low	
Confidence	Very low	Very low	Very low	Very low	Very low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation

Given the lack of information on the opportunity, there was no analysis of the costs and benefits of additional adaptation action.

N14. Risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures.

CCRA3 findings

There are a large number of pathways by which climate change could affect the outcome of these risks. While most of the focus in the literature has been on sea temperatures and species shifts (e.g. Cheung et al., 2010: Cheung et al., 2013[cxxv]), extreme temperature events are also important (Smale et al., 2019[cxxvi]). The potential impacts of climate change on fisheries may be direct (on landed species) or indirect, through the ecosystem, for example affecting species lower down in the food chain or changing marine habitats. Ocean acidification also poses a major threat to shellfish species (Mangi et al., 2018[cxxvii]) and climate change could also have impacts on fishing activities (distance travelled) and safety at sea (marine storms) (Woolf et al, 2013[cxxviii]). It is stressed that these impacts need to be seen against the background of existing fishing activities that dominate many fish stocks, i.e. climate change is an additional threat multiplier, and further, that the analysis of these changes is uncertain.

Valuation

The gross value added (GVA) for fishing has fluctuated in recent years. In 2017, GVA for fishing stood at £795 million. In 2017, the UK fishing industry had 6,148 fishing vessels, with an estimated 11,692 fishermen in 2017. In 2017, UK vessels landed 724 thousand tonnes of sea fish (including shellfish) with a value of £980 million. The UK marine fishing industry was worth ca. £1.53 billion in 2017 (POST, 2019). There is also some information on value in the ONS natural capital accounts (ONS 2019[cxxix]). The value of fish capture (commercial and recreational) is calculated using net profit per tonne (landed) estimates, provided by Seafish, for different marine species. Between 2015 and 2016, the value of marine fish capture in UK waters increased by over three quarters, from £184.1 million to £323.8 million in 2016. This was primarily caused by an increase in the value of fish capture in Scotland.

Climate change is likely to impact on the marine environment and ecosystems services these provide, thus affecting the secondary goal of protecting the wider marine environment. These changes are projected to lead to alterations in fish populations: sizes, juvenile recruitment, and geographical distribution, affecting maximum sustainable yield and catch potential (Barange et al., 2018[cxxx]) in the UK. There are also likely to be impacts on fishing fleets: distance travelled, catch type, and values of catch (Frontier, 2013[cxxxi]). The overall net impact could be positive or negative and will vary by marine zone.

Studies on climate change impacts on fisheries in the UK indicate that on average, changes in catch potential for species could range from -15% to -18% on a 2°C degree pathway by mid- and end- of century respectively (RCP 2.6); and -18% and -35% by mid- and the end of century under a 4°C pathway (RCP 8.5) compared to current levels (Barange et al., 2018).

There is some literature that provides some further quantitative data on marine fishery impacts. Fernandes et al. (2017[cxxxii]) modelled the potential effects of ocean warming and acidification on fisheries catches, resulting revenues and employment for the different nations in the United Kingdom under different climate scenarios (RCP2.6 and 8.5, with a comparison of SRES A1B). The figure shows that stock biomass are projected to decrease significantly by 2050, the main driver of this decrease being sea surface temperature rise. Overall, this shows that losses in revenue are estimated to range between 1% and 21% in the short-term (2020 to 2050) with England and Scotland being the most negatively impacted in absolute terms. The authors also estimate losses in total employment (fisheries and associated industries) of up to 20% during 2020 to 2050 with the small vessel (less than 10 m) fleet and associated industries bearing most of the losses.

The analysis was undertaken at the DA level. As an example, the analysis found that for England, the high-emission scenario would have the most significant negative impacts by 2090s, for demersal and pelagic fish (-15%), and most significantly for shellfish (-40%). A lower emission scenario would involve decreases up to 30% whereas a higher emission scenario could drive decreases of up to 60%. Indeed, the majority of impacts are revenue losses rather than revenue gains. The exceptions are in Scotland where there are economic benefits under a low emission scenario in the 2090s and under a high emission scenario in the 2020s, as a result of Northward shifts in the ranges of some warm water demersal fish species. England bears the majority of the total UK economic losses across the climate scenarios and time periods. Losses in Northern Ireland are projected to centre on shellfish production whilst in Wales losses in shellfish production are counter-balanced by revenue increases in demersal and pelagic species in the deeper fisheries.

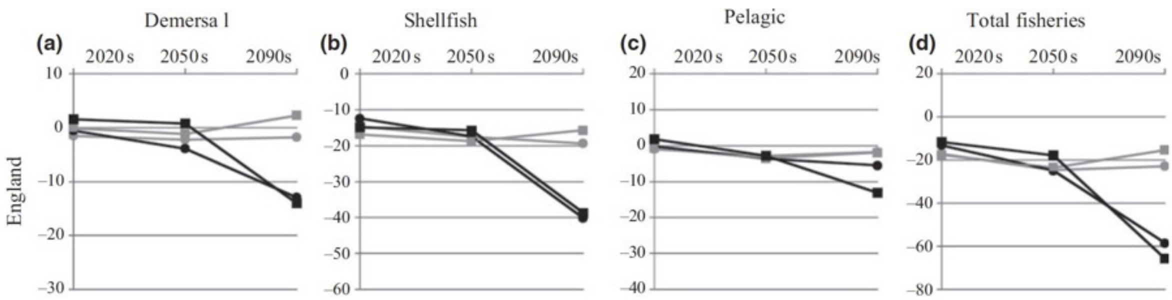


Figure 8 Percentage change in average catch potential during three ‘future’ decadal periods (2020s: 2011–20, 2050s: 2041–50 and 2090s: 2090–99) relative to the ‘present’ (1991–2000).

Source: Fernandes et al. (2017) The ‘total fisheries’ represents the effect on total catches that would occur with the projected changes in demersal and shellfish species. These results are presented for lower (RCP 2.6) [grey line] and higher (RCP 8.5) [black] emission scenarios using OAW reparameterization, and for both >10 [square] m and <10 m [round] fleet.

Table 13 Economic Costs of Climate Change on UK Fish & Shellfish Catch (£m, annual) Source Fernandes et al. (2017)

Country	CC Scenario	2020s	2050s	2090s
England	RCP2.6	59.1	71	57.3
	RCP8.5	48.3	59.6	173.1
NI	RCP2.6	7.9	8.7	9.4
	RCP8.5	7.1	7.7	8.5
Scotland	RCP2.6	0.7	14.4	-11.4
	RCP8.5	-23	1.5	169.7
Wales	RCP2.6	3.1	7	5.5
	RCP8.5	30.4	4.6	19.3
UK	**RCP2.6**	**70.8**	**101.1**	**60.8**
	RCP8.5	**62.8**	**73.4**	**370.6**

There are a number of other studies. Using cost-benefit analysis, Mangi et al. (2018[cxxxiii]) estimated the potential economic losses to UK shellfish wild capture and aquaculture under medium and high CO_2 emission for molluscs and crustaceans. They found that losses (expressed in NPVs using a 3.5% discount rate up to 2100) could reach up to £300m and £599m for molluscs; and £387m and £775m for crustaceans under medium and high emission scenarios respectively. Looking at all shellfish, in England, reduced production could range from 16% to 33% of fishery NPV. This equates to annual economic costs of between £1 and £2 billion, for medium and high scenarios. In Scotland, losses under the high scenario are greater – up to £2.5 billion, whilst in Wales and Northern Ireland they are both approximately £0.5 billion.

Table 14 Time integrated NPV by 2100 of the potential economic losses to UK shellfish wild capture and aquaculture (£m, 2013 prices)

Region	Scenario	Molluscs	Crustaceans	Wild capture	Aquaculture	All shellfish
UK	NPV with no impact of CO2	1847	4265	6995	1305	8301
	Medium Emissions	185–739	426–1279	700–2448	131–457	830–2905
	High Emissions	923–1478	1706–2559	2798–4897	522–914	3320–5810
	% loss from fishery NPV	10.6–21.1	18.3–36.6	11.8–23.6	2.2–4.3	14.0–28.0
England	NPV with no impact of CO2	749	1291	2572	466	3039
	Medium Emissions	75–300	129–387	257–900	47–163	304–1064
	High Emissions	374–599	516–775	1029–1801	187–326	1215–2127
	% loss from fishery NPV	11.6–23.3	15.1–30.1	13.8–27.7	2.5–5.0	16.3–32.7
Scotland	NPV with no impact of CO2	721	2451	3394	243	3637
	Medium Emissions	72–288	245–735	339–1188	24–85	364–1273
	High Emissions	360–576	980–1470	1358–2376	97–170	1455–2546
	% loss from fishery NPV	8.4–17.0	21.7–43.3	10.0–20.0	0.7–1.4	10.1–21.4
Wales	NPV with no impact of CO2	135	70	318	430	748
	Medium Emissions	14–54	7–21	32–111	43–151	75–262
	High Emissions	67–108	28–42	127–223	172–301	299–524
	% loss from fishery NPV	17.0–34.1	6.6–13.3	12.6–25.3	17.1–34.2	29.7–59.4
NI	NPV with no impact of CO2	76	426	508	166	673
	Medium Emissions	8–30	43–128	51–178	17–58	67–236
	High Emissions	8–61	170–256	203–355	83–116	269–471
	% loss from fishery NPV	6.0–12.0	25.2–50.3	12.1–24.3	4.0–7.9	16.1–32.2

NPV are in millions based on 2013 GB pounds sterling. The low and high end of each range are designed to show how sensitive the economic figures are to changes in biological impact. Source: Mangi et al. (2018)

For large vessels (>10m) Pinnegar et al. (2012) assessed the costs of travelling further to catch current species at £1 million to £9 million annually in the 2020s across the range of emissions scenarios; and potentially £10 million to £99 million in later periods. Small vessels are restricted from travelling and so are not as likely to be able to benefit from opportunities arising further way from the UK shoreline. Access to capital and cost of new vessels is a critical issue, especially for smaller enterprises. The Economics of Climate Resilience study (Frontier Economics, 2013) estimated a new boat can cost up to £1m, and a second hand one up to £750,000.

It is important to consider the macro-economic effects and trade to fully understand the potential economic costs or benefits of climate change on fisheries. The EC COACCH study (2020) projected combined global biophysical models with a CGE model. This projected that catch potential will decrease significantly in tropical waters but have less impact on catch and thus productivity in Europe. All Member States are projected to experience declines in marine productive capacity, with the most serious impacts occurring in Denmark, Spain, France, and the UK. However, the consideration of international price effects leads to an interesting effect: while there is a direct impact of climate change on the fish stocks in Europe (the RCP 8.5 and high impact are negative across all the coastal regions), there are positive GDP gains due to trade effects with non-EU countries. EU regions generally experience gains, though they are not found to be significant in terms of GDP changes.

Valuation summary

There is a large range depending on the study chosen, and assumptions, which can even vary in sign. This makes it very difficult to provide central values. The values also change depending on the boundary conditions, i.e. whether the potential for trade effects, are considered, as this tends to lead to more positive outcomes, due to the greater impacts in other world regions.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
England		Range from medium positive to medium impact	Range from medium positive to medium impact	Range from medium positive to medium impact	Range from high positive to high impact	Not known
Northern Ireland		Range from low positive to low impact	Range from low positive to low impact	Range from low positive to low impact	Range from medium positive to medium impact	
Scotland		Range from medium positive to medium impact	Range from medium positive to medium impact	Range from medium positive to medium impact	Range from high positive to high impact	
Wales		Range from low positive to low impact	Range from low positive to low impact	Range from low positive to low impact	Range from medium positive to medium impact	
Confidence		Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation

Many of the same options as identified for the risks to marine species and fisheries (previous risk) are also relevant for this opportunity, for realising the potential economic benefits. This includes the capacity building in the industry, and the switch to an adaptive management approach for the fisheries sector, with a scale up in monitoring, scientific information and awareness raising, subsequently including this information in regular updates of fisheries policy (e.g. to set maximum catch potential for current species, include new species in policy) alongside awareness raising in the fishing sector. The CCC outcomes study (Watkiss et al., 2019) assessed that such an adaptive management strategy would have positive benefit to cost ratios, through the value of information and enhanced decisions taken. It is highlighted that there is a role for government in awareness raising for the fishing sector and for consumers, and enhanced monitoring of new species will require action by the public sector. Previous studies have also highlighted there is a need to target awareness and support in the fishing sector, to ensure opportunities are realised by small vessel operators, given their adaptive capacity will be lower (Frontier Economics, 2013[cxxxiv]).

N15. Opportunities to marine species, habitats and fisheries from changing climatic conditions

CCRA3 findings
Chapter 3 of the CCRA summarised the evidence on this risk. The arrival of warm water species into UK waters provides new opportunities for biodiversity and fisheries. These benefits will rise over time. Over the last 20 years, there have been expanding fisheries for warmer water species such as seabass and red mullet and new opportunities are developing for species such as Atlantic bonito, jack, and bluefin tuna. The response to warming will be strongly influenced by individual species physiology and its thermal tolerance range, which may be further modified by phenotype acclimation (over the lifespan of the individual) and evolutionary adaptation (over multiple generations).

Valuation
The potential opportunities are outlined in the previous risk: there are some potential species for which positive gains are expected. Jones et al. (2013[cxxxv]) used the estimates from three species distribution models for 14 commercial fish in the Northeast Atlantic to look at the UK EEZ, under an IPCC A2 scenario. They projected poleward shifts at an average rate of 27 km per decade. This identified changes in habitat suitability and latitudinal centroid shift. The largest gains were for European squid, sea bass and sprat, but there were also increases in some high value species.

At the same time, the CGE modelling in COACCH (2020) finds that because impacts of fisheries are even greater globally, there could be net positive effects from climate change for UK fisheries from climate change. This indicates quite large economic benefits. There are two issues of relevance for valuation. First, the increased catch potential of some new species, due to migration. Second, the potential economic benefits from the comparative advantage of UK coastal waters compared to production areas globally, and thus price and trade effects. Separate valuation estimates for this risk are not included here – but are reflected in the score for fisheries above.

N16 Risks to marine species and habitats from pests, pathogens and invasive species

CCRA3 findings
Chapter 3 of the CCRA Technical Report summarised the evidence on this risk. The risk assessment finds that climate change provides increased scope for the establishment and spread of invasive and pest (problem) species as well as pathogens that may harm biodiversity, commercially important marine species and human health. The linkages between climate change and such impacts are, however, difficult to isolate from other non-climatic influences such as ocean pollution and trade patterns. There is considerable uncertainty around risks to marine species from pests, pathogens and INNS due in a large part to the scale and complexity of the marine environment.

Valuation
Marine invasive non-native species (INNS) are a threat to biodiversity and have important potential ecosystem service impact, particularly with regard to commercial fisheries and aquaculture (provisioning services). There is some information on control (adaptation) costs. The Carpet Sea Squirt, which is highlighted in the risk assessment as preferring warmer waters - is known as a marine fouling organism that has recently spread to the UK where there have been a number of recent outbreaks in ports. Williams et al, 2010[cxxxvi] estimate the cost of eradication of the current UK population from marinas was placed at £2.4 million. If the Carpet Sea Squirt were to spread to all UK marinas, then the overall cost of eradication could rise to £72 million. Williams et al. also estimated the total eradication cost for these outbreaks to be just under £1 billion, though this seems extremely high. There is no information as to the frequency of such outbreaks under climate change scenarios so that is not possible to calculate AADs, though these are clearly potentially sizeable. It should also be noted that these are cost-based measures so do not capture people's willingness to pay to avoid marine INNS. More broadly, Williams et al estimate total annual costs associated with INNS in relation to aquaculture. They estimate an annual cost of £4.4 million in England, £0.8 million for Scotland, and £2.2 million for Wales. In the absence of data for Northern Ireland we speculate that the total will be similar to Scotland, based on the size of its fishing industry – perhaps £1 million.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	Medium	Medium	Medium	Medium	
Confidence		Very low	Very low	Very low	Very low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

N17. Risks and opportunities to coastal species and habitats due to coastal flooding, erosion and climate factors

CCRA3 findings

The risk assessment considers these risks together as they are seen as inter-related and co-evolving processes associated primarily with sea-level rise. The magnitude of risk to coastal species and habitats is projected to increase, though the change is influenced by the rate and magnitude of sea level rise. The main impact of these risks is loss or degradation of natural habitat, including salinisation. Areas of accretion also represent habitat creation opportunities though these are localised in a small number of estuaries. Warm-favouring species, e.g. of shell-fish, are projected to continue to expand their ranges, whilst for a number of sea-birds their numbers are projected to be in decline possibly due to a mis-match between their food source availability such as sand-eels and a change in life-cycle timings of these organisms.

Valuation

The UK National Ecosystem Assessment cited one study (COREPOINT, 2007) that assessed the total value of coastal ecosystem services as worth at least £48 billion, whilst the ONS (2016) prototype methodology for ecosystem accounts provided an indicative net present value over 50 years of £22.7 billion, (currently equivalent to circa £1 billion per year), based upon those services that are more easily quantified.

Sayers et al (2020[cxxxvii]) estimated coastal flood to designated areas, and this was presented in the CCRA3 research reports. These values have been monetised in this study, to estimate the potential associated damage costs. For each country we assume that the hectarages labelled as “Most important habitats exposed to frequent flooding” have – or are equivalent to having – SSSI status. The flood risk is assumed to be 1 in 100 years. Monetary valuation is taken from the results of a choice experiment undertaken to derive willingness to pay to maintain habitats at the levels required by Sites of Special Scientific Interest (SSSIs) (Christie and Rayment, (2012)). A central value of £10,000 per hectare is derived from this study as the willingness to pay to avoid the loss of intertidal mudflats and saltmarsh with SSSI status. These data generate the results presented below, i.e. the costs associated with flood risk in the baseline, current, period, and the additional costs projected under climate change projections as a result of greater hectarages being vulnerable to flood risk.

Table 15 Annual Coastal Flood Risk Costs for Most important Habitats – Baseline & Climate Change (£) Source authors, based on habitat change in Sayers et al., 2020

	Baseline costs	**Additional annual climate change-induced costs (£)**			
		2050s 2C	**2080S 2C**	**2050s 4C**	**2080s 4C**
England	4,843,400	2,760,738	3,099,776	3,148,210	3,341,946
N. Ireland	107,800	19,404	35,574	40,964	59,290
Scotland	6,978,400	139,568	209,352	279,136	348,920
Wales	4,000,600	920,138	1,120,168	1,120,168	1,280,192

There are some other models that estimate coastal wetland loss, notably the DIVA model. This has produced global (Schuerch et al., 2018[cxxxviii]) and European estimates of losses from climate change

(Brown et al., 2011[cxxxix]). The latter study suggests that 35% of coastal wetland area in Europe could be lost by the end of the 21st century, but these estimates are not expressed in terms of monetary values.

The valuation summary is presented below. The level of evidence is low, especially as this risk involves all coastal species and habitats.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
England	Low	Medium	Medium	Medium	Medium	
N. Ireland	Low	Medium	Medium	Medium	Medium	
Scotland	Low	Medium	Medium	Medium	Medium	
Wales	Low	Medium	Medium	Medium	Medium	
Confidence		Very low	Very low	Very low	Very low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

Adaptation
There are some studies which include the impacts (in economic terms) of climate change on some coastal habits notably wetlands (e.g. see Brown et al., 2011: Schuerch et al., 2018[cxl]), but these studies do not assess the costs and benefits of adaptation. There are also studies that look at the role of coastal ecosystems for ecosystem-based adaptation, with analysis of costs, cost-effectiveness analysis and cost benefit analysis (Narayan et al. 2016[cxli]: ECONADAPT, 2017[cxlii]: McVittie et al., 2017[cxliii]). However, there is much less information on the costs and benefits of helping coastal species adapt, and there may also be trade-offs with measures to protect the built environment having consequences on species (coastal squeeze). Early low-regret options tend to focus on improved information and monitoring, but there are other measures including possible reinforcement or enlargement of existing measures, e.g. protected areas, buffer zones, as well as restoration of areas or managed realignment, and there are some estimates of restoration costs from previous projects.

N18. Risks and opportunities from climate change to landscape character

CCRA3 findings
Chapter 3 of the CCRA summarised the evidence on this risk. Future changes to landscape character will occur from a range of natural responses to a change climate including biodiversity, soils, hydrological processes and coastal processes

Valuation
Climate change may bring about changes in landscapes to which people attach values, i.e. there are a range of potential impacts on cultural services (Recreation, Aesthetic, Sense of Place, Cultural Heritage). However, there is the potential for overlap with previous risks and opportunities.

There are a range of monetary values relating to landscape established in Government project appraisal – see those proposed for use in transport projects by the Department for Transport WebTag guidance (WebTag, 2016[cxliv]). However, it is not possible to apply these, as the risk assessment finds that quantification of climate change effects has not yet been undertaken.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Unknown	Unknown	Unknown	Unknown	Unknown	
Confidence	Very low	Very low	Very low	Very low	Very low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3).

<u>*Adaptation*</u>
This is a very large risk / opportunity and it is difficult to cover the costs and benefits of adaptation without more detailed and disaggregated analysis. In general terms, enhanced monitoring would be a low-regret option, especially as part of adaptive management. There are an existing set of measures for conservation, landscape restoration, etc. with cost estimates, but it is more difficult to assess the marginal actions needed to address climate change risks.

Summary of the Natural Environment Theme Valuation

This chapter has investigated the monetary valuation of the natural environment theme. The findings are summarised in the table below. A number of key findings emerge from the analysis.

The focus of the valuation for natural environment here is on ecosystem services, i.e. on the provisioning, regulating, cultural and supporting services they provide. However, the natural environment, and the quantification and valuation of ecosystem services, presents a considerable challenge. Indeed, for 5 of the 18 risks, it was not possible to attach any robust valuation scores.

Valuation is easiest (and there is most evidence) for the provisioning services e.g. agriculture, forestry and fisheries, where market prices exist. The analysis of the risks of climate change to these provisioning services indicate potentially high or very high economic costs (£billions/year) to the UK, even by mid-century. However, there are wide differences in the evidence on these risks. Sometimes this is due to the physical impact studies: for example, studies that assess changes in extreme events tend to find more significant negative impacts than studies that only include slow-onset impacts. They also vary according to whether positive aspects are included, notably CO_2 fertilisation.

Interestingly, a further difference is found between studies that focus on physical impacts (and then value changes in production) versus studies that then input these results into economic models. Studies that use partial equilibrium or general equilibrium analysis extend beyond physical metrics (yield) to look at markets, trade and prices, and these generally project much more positive outcomes for the UK, indicating high or very high positive benefits. This is because of the comparative advantage that the UK is projected to gain, as climate change impacts are projected to be larger in many European and international countries. However, while this is positive, these opportunities may not be realised, or limited, due to competing priorities for land and water from other uses and users. There are also unknowns regarding the effects of Brexit on international trade. The wide range of possible outcomes is indicated in the table below, notably for NE6 and NE14/15.

For the regulating services, the effect of climate change on natural carbon stores (NE5) – most notably in soil, trees and seagrass – maybe significant. For example, changes in temperature and precipitation patterns are likely to reduce the ability of soils to retain carbon and so result in carbon emissions. It is possible to quantify these emissions and consider the value of carbon sequestration. Using these approaches, there is the potential for the risk to be Very High. However, there is high uncertainty with the physical pathways and interactions for this risk. It should also be noted that water resources are also a critically important regulatory service but are discussed in relation to infrastructure and health chapters.

Quite a large number of CCRA3 risks are focused on pests and diseases (NE2, NE7, NE8, N12, NE16). These are generally assessed as having low or medium impacts, but it is highlighted that this assumes some level of management and control. It was found that these scores could change to high or very high scores if particularly damaging non-invasive species become endemic.

There is a major gap on the valuation of cultural and supporting services, represented by unknown scores in the table above. We suspect that many of these categories would give rise to high or very high valuation scores (i.e. £billions/year), but there is simply not sufficient quantitative risks evidence to assess these in monetary terms. This is a concern because it underestimates the overall economic impacts, and may give the impression that impacts for the natural environment are lower than other themes. We do not believe this is the case.

A number of other insights emerged from the analysis. There is less literature available (than for other themes) on the influence of future socio-economic change on the natural environment, however, it is clear that these changes are extremely important. They include potential changes in land-management, as well as agricultural, forestry and fisheries policy, all of which could have a significant influence on the nature and size of future impacts. This now also includes the very major changes that will need to happen to land-use to deliver the UK's Net Zero commitment (by 2050). For example, the Net Zero commitment may result in a move away from pastoral grazing lands that support the rearing of livestock for human consumption, and towards meadowlands and forestry that facilitate carbon sequestration. This would affect the risks and opportunities from climate change on agriculture and forestry, but also the potential for risks and opportunities from climate change on carbon storage (NE5).

There is also less literature on the influence of current and planned adaptation for the natural environment, and the analysis is complicated by what is assumed about natural acclimatisation, as well as thresholds. The evidence does indicate that impacts will rise disproportionately for the natural environment at higher warming, but there is not the evidence to report on exactly when these non-linearities occur. This is shown by higher scores for the 4°C pathway in the table, though this does not fully capture the possible step changes in the scale of impacts that might occur. We therefore caution about reading the results above too positively. There is also a question of the effects of multiple risks acting together on the natural environment, i.e. this is one area where considering risks individually does not give the full picture. This fact is, therefore, supportive of the use of the natural capital approach to understanding the aggregate effect of climate change risks on the natural environment (Dasgupta, 2021)[cxlv].

Overall, while there is more evidence on the monetary valuation of natural environment risks and opportunities than was available in CCRA1, there remains a major evidence gap for the valuation of the natural environment theme. However, we stress that this is often due to a lack of quantitative information on risks (or opportunities) rather than the valuation step, i.e. the biggest gap is the evidence on what level of physical impacts will occur from climate change. It is also noted that it was often much harder to value the risks and opportunities for this theme in CCRA3 than it was in CCRA1, because CCRA3 groups risks and sub sectors together. Given all of this, we recommend that further work into the quantification and valuation of these risks should be prioritised. Given the location-specificity of many of the risks, this might be advanced through case studies (e.g. for different risk categories and different habitats), which could then be aggregated to provide indicative aggregate estimates

Table 16 Summary of Natural Environment Valuation Scores. UK level. Central Estimates.

	Risk/Opportunity	Present Day	2050s, on a to pathway stabilising at 2°C by 2100*	2050s, on a pathway to 4°C at end of the century#	2080s, on a to pathway stabilising at 2°C by 2100*	2080s, for 4°C world at the end of the century#	Confidence
N1	Risks to terrestrial species and habitats from changing climatic conditions and extreme events	Not known	Not known	Not known	Not known	Not known	Very low
N2	Risks to terrestrial species and habitats from pests, pathogens and invasive species	Not known	Not known	Not known	Not known	Not known	Very low
N3	Opportunities from new species colonisations in terrestrial habitats	Not known	Not known	Not known	Not known	Not known	Very low
N4	Risk to soils from changing climatic conditions, including seasonal aridity and wetness.	High (England) / Medium (Other DA)	High (England) / Medium (Other DA	High (England) / Medium (Other DA	High (England) / Medium (Other DA	High (England) / Medium (Other DA	Very low
N5	Risks to natural carbon stores and sequestration from changing climatic conditions	Very high (England and Scotland)	Very high (England and Scotland)	Very high (England and Scotland)	Very high (England and Scotland)	Very high (England and Scotland)	Low - medium
N6a	Risks to and opportunities for agricultural productivity from extreme events and changing climatic conditions	High	Range from High positive to High negative	Range from High positive to High negative	Range from Very High positive to Very High negative	Range from Very High positive to Very High negative	Low
N6b	Risks to and opportunities for forestry productivity from extreme events and changing climatic conditions		Range from low to high	Range from low to high	Range from low to high	Range from low to very high	Low
N7	Risks to agriculture from pests, pathogens and invasive species	Medium	Medium	Medium	High	High	Low
N8	Risks to forestry from pests, pathogens and invasive species	Medium	Medium	Medium	Medium	High	Low
N9	Opportunities for agricultural and forestry productivity from new/ alternative species becoming suitable.	Medium	+High	+High	+High	+Very high	Low
N10	Risks to aquifers and agricultural land from sea level rise, saltwater intrusion	Low	Not known	Not known	Not known	Not known	Very low

N11	Risks to freshwater species and habitats from changing climatic conditions and extreme events	High	High	High	High	High to Very high	Low
N12	Risks to freshwater species and habitats from pests, pathogens and invasive species	Low	Low	Low	Low	Medium	Very low
N13	Opportunities to freshwater species and habitats from new species colonisations	Low	+Low	+Low	+Low	+Medium	Very low
N14	Risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures.		Range from medium positive to medium impact	Range from medium positive to medium impact	Range from medium positive to medium impact	Range from high positive to high impact	Low
N15	Opportunities to marine species, habitats and fisheries from changing climatic conditions		Included in above	Included in above	Included in above	Included in above	Low
N16	Risks to marine species and habitats from pests, pathogens and invasive species	Low	Medium	Medium	Medium	Medium	Very low
N17	Risks and opportunities to coastal species and habitats due to coastal flooding, erosion and climate factors	Low	Medium	Medium	Medium	Medium	Very low
N18	Risks and opportunities from climate change to landscape character	Unknown	Unknown	Unknown	Unknown	Unknown	Very low

Very high = £billions/year.
High = £hundreds of millions/year.
Medium = £tens of millions/year.
Low = £<10 million/year.
DA values are presented as absolute values (not relative scoring as in CCRA3).

Infrastructure

The list of risks and opportunities for the infrastructure chapter (Chapter 4) of the CCRA3 Technical Report is shown below.

Risk
I1. Risks to infrastructure networks (water, energy, transport, ICT) from cascading failures
I2. Risks to infrastructure services from river, surface water and groundwater flooding
I3. Risks to infrastructure services from coastal flooding and erosion
I4. Risks to bridges and pipelines from flooding and erosion
I5. Risks to transport networks from slope and embankment failure
I6. Risks to hydroelectric generation from low or high river flows
I7. Risks to subterranean and surface infrastructure from subsidence
I8. Risks to public water supplies from reduced water availability
I9. Risks to energy generation from reduced water availability
I10. Risks to energy from high and low temperatures, high winds, lightning
I11. Risks to offshore infrastructure from storms and high waves
I12. Risks to transport from high and low temperatures, high winds, lightning
I13. Risks to digital from high and low temperatures, high winds, lightning

Infrastructure is recognised as an increasingly important area for climate risk assessment in general. This is because of a number of reasons.

First, infrastructure has a long lifetime (decades) and could be exposed to potentially large future climate change impacts over its lifetime. This may result in impacts on assets (risk of damage or failure), operating costs and performance, including the benefits or services provided. These risks are particularly important when considering priorities for the next five years (as CCRA3 aims to do), because new investment in infrastructure projects involves potential lock-in[6] or irreversibility and it is often easier and more cost-effective to build resilience (adaptation) during design than retrospectively (Fankhauser et al., 1999[cxlvi]: Ranger et al., 2010[cxlvii]). The scale of this lock-in risk is important: the average annual investment set out in the National Infrastructure Delivery Plan is £48 billion/year (IPA, 2016[cxlviii]).

Second, in addition to the direct risk of damage and disruption of individual assets, there is a risk of indirect or cascading impacts associated with infrastructure, and especially critical infrastructure. Activities and services such as heating, lighting, mobility and water are essential for modern society and they increasingly rely on each other, for example from interdependencies and interconnectivities with electricity and information and communication technology (ICT). Damage to critical infrastructure in one sector or geography can therefore lead to important indirect (cascading) economic losses through interdependent infrastructure linkages (Hallegatte et al., 2019[cxlix]).

Finally, climate risks are now recognised as a financial risk as with the Task Force on Climate-related Financial Disclosures (TCFD, 2017[cl]), and the Network for Greening the Financial System (NGFS, 2019[cli]). These aim to improve the integration of climate risks into decisions, and much of this has been focused on infrastructure risks. Importantly, infrastructure developers and operators are required to plan and manage assets in a long-term perspective - or at least for the duration of the concession period of the private-public partnerships (PPPs) (typically 25-30 years). This should mean they have a relatively greater to incorporate climate change risks into decision making, from design to operation and maintenance.

[6] An action or decision today that 'locks-in' the potential for future climate risk and is difficult or costly to reverse or change later. This includes decisions or investments that involve a long lifetime, the potential for large future climate risks and a degree of (quasi) irreversibility. Note lock-in may arise from an action or decision taken that is 'business-as-usual', from a lack of an action or decision, or from a mal-adaptative action or decision. Source CCRA3 definitions, Chapter 2.

The main approach taken in this chapter is to try and value the flow of services that are derived from the stock of capital (infrastructure). However, in many cases, there is a lack of information to allow this, and most literature is focused on the impacts to physical stock. It is also highlighted that impacts on infrastructure are also an important factor in economic output, and this can be assessed using macro-economic analysis. This is important because climate change could affect drivers of growth, e.g. through capital stock destruction, which could affect economic growth rates. Such effects could lead to large cumulative economic effects from climate change over time[clii], which are much larger than from annual impacts assessed below.

I1. Risks to infrastructure networks (water, energy, transport, ICT) from cascading failures

Chapter 4 of the Technical Report identifies that infrastructure operates as a system of systems, which means that vulnerabilities on one network can cause problems on others, and indeed extend beyond the infrastructure sector or the immediate location. The report finds that given the wide-ranging nature of the linkages, a full understanding of the impacts of cascading failures is difficult to ascertain. However, it cites international research, which has indicated that the vulnerability of interconnected systems may be significantly underestimated. The Technical report does include a list of cascading impacts, such as flooding causing power infrastructure inundation, or power supply interruption leading to impacts on travel and freight operations.

<u>Valuation</u>
There are a number of different types of cascading risks, and these reflect different potential economic impacts. CCRA2 defined these as (Street et al., 2017[cliii]):

- Interaction among risks; and
- Indirect and macroeconomic impacts.

We use this categorisation, though we note that the CCRA3 Technical Report identifies a more differentiated set of types of linkages, especially for infrastructure. This is reflected in the literature, for example, network interdependencies are grouped by Pant et al., (2020[cliv]) into physical connections, cyber/information linkages, geographic / proximity and logical linkages.

The indirect impacts of major weather-related events have been found to have high economic costs (currently), for example from the impacts on the transport network affecting travel time, or supply and business interruptions leading to lost productivity and affecting revenues.

Major events can also potentially affect the economy as a whole, and can cascade through to other sectors of the economies and other regions beyond those initially affected. The impacts on infrastructure are a key part of these wider economic effects (Hallegatte et al., 2019[clv]). For very large extreme events (e.g. major floods or storms), these indirect costs and macro-economic costs can be as large as the direct damage (Hallegatte and Przyluski, 2010[clvi]). For infrastructure specifically, the ratio of indirect impacts (relative to direct impacts) have been found to be significant, and increase with the size of the event, but even for relatively short disruptions, losses can be substantial and spread across all sectors For example, Pant et al., (2014clvii) estimated 3-day aggregated losses for three hazard events, that trigger direct losses in the economy due to electricity and railway network failure, and indirect losses that propagate to other sectors that are dependent on these. In their model, indirect costs represent more than half of total costs. Another example is from a study on major floods in London, which estimated that indirect effects increase in magnitude (in £) and exceed direct costs for very large extreme events: indirect losses are a significant component of total losses, with a multiplier of between 1.3 and 2 depending on the scale of initial damage (Crawford-Brown et al., 2013[clviii]).

The focus of this risk is on the economic costs of the impact of the cascading effect, i.e. on the connected systems, e.g. the transport costs caused by an electricity outage, or the wider economic costs of a flood on properties leading to impacts in other sectors. However, there is also an issue on where to report these impacts, as some are captured elsewhere in this chapter (e.g. indirect effects of flooding for the transport infrastructure) and some in other chapters including in Chapter 5 (people) and Chapter 6 (business). It is important to avoid double counting of costs. At the same time, it is noted that because CCRA3 focuses on individual risks and opportunities, it may miss some wider economic and especially macro-economic effects.

There is a small body of quantitative literature that looks at the current impacts of cascading risks. Under future climate change scenarios, more frequent and more intense weather-related events are likely to increase the risk of infrastructure and network impacts, leading to potentially significant socio-economic costs. However, estimating the risk of failure of infrastructure (and infrastructure networks) and the indirect and cascading impacts is a challenging task, and thus, there are limited studies. This is because different infrastructure assets are exposed to different weather-related risks to various extents, and the cascading effects vary upon the degree of the inter-connectiveness and inter-dependency amongst them.

The CCRA2 infrastructure chapter (Dawson et al., 2016) reported a number of cascading impacts. This included the flooding of substations at Gatwick in December 2013 that resulted in the disruption of 13,000 airline travellers. The total costs included welfare costs of £3.0 million (range £2.4 million to £3.6 million) comprised of the estimated cost to passengers resulting from travel delays and disruption caused by flooding (Chatterton et al., 2016)[clix].

The CCRA3 infrastructure chapter identifies a further number of cascading failures, including the power outages in England and Wales in August 2019 caused by a lightning strike, which had significant knock-on impacts for the rail sector, with stranded trains, triggered by on-board automatic safety systems, and in turn, knock-on delays across the rail network. 31 trains were stranded, and passengers had to be evacuated. There were substantial knock-on delays following recovery of the vehicles, totalling 14,428 minutes (ORR, 2020[clx]). Full service was restored within 24 hours. Following that event, three energy firms have agreed to pay a total of £10.5m into a redress fund run by the UK's energy watchdog, Ofgem[clxi]. It also gives the examples of the flooding of an electricity substation in Lancaster from Storm Desmond in December 2015, that left the city without power for more than 30 hours and had consequences for transportation, telecommunications (no mobile network, internet or digital radio), and water supply in some areas. The total cost of Storm Desmond and Eva (in 2015) have been estimated by PwC at over £1bn, with the insurance industry paying out the majority of these costs[clxii]. In 2018, the EA[clxiii] estimated the costs resulting from the winter floods in England following Storms Desmond, Eva and Frank at £1.6 billion. A sizeable proportion of these costs were indirect.

The National Infrastructure Commission (NIC, 2020[clxiv]) also describes a number of UK cascading failures in the UK from weather-related events. This included the 2007 floods, which affected electricity substations and water treatment plans and water supply. It also reported on the Lancaster winter floods of 2015/16 (due to Storm Desmond), and on the cascading impact on communication services, transport and businesses, as well as the power outage in 2019 (due to a lightning strike) which affected train operating companies, hospitals, water treatment plants and an airport. However, no attempt was made to estimate the socio-economic losses that resulted from the above events.

Most of the evidence on cascading risks which looks at the potential economic costs focuses on two sectors: transport and electricity, and primarily with respect to floods. There are a number of global and national studies that look at the transport sector, and consider the indirect effects of transport disruption (Koks et al., 2019[clxv]: Oh et al. 2020[clxvi]). The immediate indirect effects (impacts on travel time) are captured in the subsequent risk on transport infrastructure (I2 and I3). The impacts on electricity generation from floods have also been considered, in terms of the lost electricity for consumers, but also includes some studies on cascading risks. The direct costs of outages are captured by estimates of the value of lost load, covered in I2 and I10.

A recent study by Pant et al. (2020[clxvii]) was commissioned by the National Infrastructure Commission to pilot an approach to assess the key physical vulnerabilities of the current UK infrastructure system, draw out vulnerabilities that arise from network architecture and how these could change in the future, and inform the development of a framework to identify actions to assess, improve and monitor system resilience. The study developed a system-of-systems modelling approach with national-scale network representations of electricity, road and rail transport, public water supply and digital communication networks, capturing their interdependencies. The authors first considered the case where networks are connected such that each dependent node of one network is linked to only one node of the other network (i.e. single degrees of connections, with no back up). From the cumulative user disruptions estimated for this baseline case, the authors selected the top 50 most severe events, on which they then tested five resilience enhancing options such as: two connections (i.e. connecting each dependent node of one network to two nodes of the supplying network), three connections, backup (assuming that some assets had backup electricity supply), and a combination of two/three connections and backup supply. The aim of adding more connections was to test the benefits of adding more redundancy between networks. The study focussed on the failure events initiated by the electricity and also by the telecoms network (though the study did not specifically look at the role of weather-related events in causing/triggering infrastructure failures). A failure in the study is modelled by removing an individual node (single point of connection) from a network and estimating the cascading effect that would follow.

Failure events initiated in each network were quantified in terms of direct economic losses and indirect economic losses. The latter used an Input-Output (IO) model (assuming service disruptions lasted for 24 hours) to look at indirect economic losses to all sectors that use electricity, telecoms and railways outputs. The direct demand losses relate to the customer disruptions. To demonstrate the failure model and its results, the authors first show *an example* of failure event initiated in the electricity network and with single dependencies between networks. Assuming the disruptions last for 24 hours, the economic losses correspond to losing demand from the equivalent of 24 hours of customers across sector. The indirect losses for electricity were estimated to be almost as high as direct losses due to feedbacks from the rest of the economic systems. The sector 'Other' (which dominates indirect costs) corresponds to the total losses added across all 124 non-infrastructure sectors in the UK economy, estimated at £345,000/day indirect economic losses. Overall, this shows that the economic impact of a major failure event initiated in the electricity sector could be worth £0.9 million/day total economic losses.

Table 17 Total economic losses resulting from an *example* failure event initiated in the electricity sector (single dependencies) and lasting 24h (Pant et al. 2020).

Network/Sector	Direct economic losses (£/day)	Indirect economic losses (£/day)	Total economic losses (£/day)
Electricity	131,507	98,699	230,206
Telecoms	71,233	4,575	75,808
Rail	260,274	636	260,910
Water	0	286	286
Road	0	6,667	6,667
Others	0	345,069	345,069
Total	**463,014**	**455,932**	**918,946**

The multiplier effects used in the analysis are estimated by the Office of National Statistics and are useful as they show the ratio between the total economic losses and the demand losses in a particular sector. For example, for every 1 unit of direct demand losses in the electricity sector there are total economic losses of 2.36 units. These multiplier effects show that electricity has the highest multiplier effects.

Table 18 Infrastructure networks specific economic sectors and their multiplier effects (Pant et al., 2020)

Economic sector	Multiplier effect
Telecommunications services	1.41
Electricity, transmission and distribution	2.36
Natural water; water treatment and supply services	1.53
Land transport services and transport services via pipelines, excluding rail	1.64
Rail transport services	1.95

The study looked at the direct and indirect losses for the top 50 24h-failure events - in terms of the cumulative user disruptions as estimated by their failure model – initiated by the electricity sector. The figure below shows error bar plots with the mean values and 95% confidence intervals for economic losses averaged across all top 50 user disruption events for failures initiated by the electricity network and considering only single degrees of connections. The results show the direct and total economic losses for the infrastructures specific sectors and the rest of the economy (‘Other’ sectors). In this case, the direct costs varied between £0.36 million/day – £3.4 million/day and total losses vary between £0.58 million/day – £6.7 million/day. The authors point out that the economic losses and user disruptions might not be similarly ranked for failure events, i.e., the largest user disruptions might not result in the largest economic losses. This is due to the significant impact of railway when failure in one node typically has a knock-on effect and lead to cancellations of entire train journeys, with significant economic impacts due to the reduced capacity of the sector to meet journey demands. As explained by the authors, user disruptions are the highest in the water network. This is because the water supply network has very high user demands concentrated at individual nodes. The largest economic losses are, however, recorded in the railways sector, which are as high as £2.7 million/day, from reduced capacity to meet journey demands.

Similar results are reported for failure events initiated in the telecoms network with single degrees of connections (not shown): direct losses for the top 50 events vary between £0.22 – £3.6 million/day and total losses vary between £0.34 – £7.0 million/day, with the event specific total losses being 1.52 – 1.99 times the direct losses (not shown). In this case, the model shows that the largest user disruption event of 7.2 million user disruptions has about £2.1 million/day economic losses. Importantly, the model also shows that a higher number of disrupted users is not necessarily indicative of higher economic impacts: disruptions to the railway sector with less than 3 million user affected produce the highest economic impacts of up to £2.5 million/day.

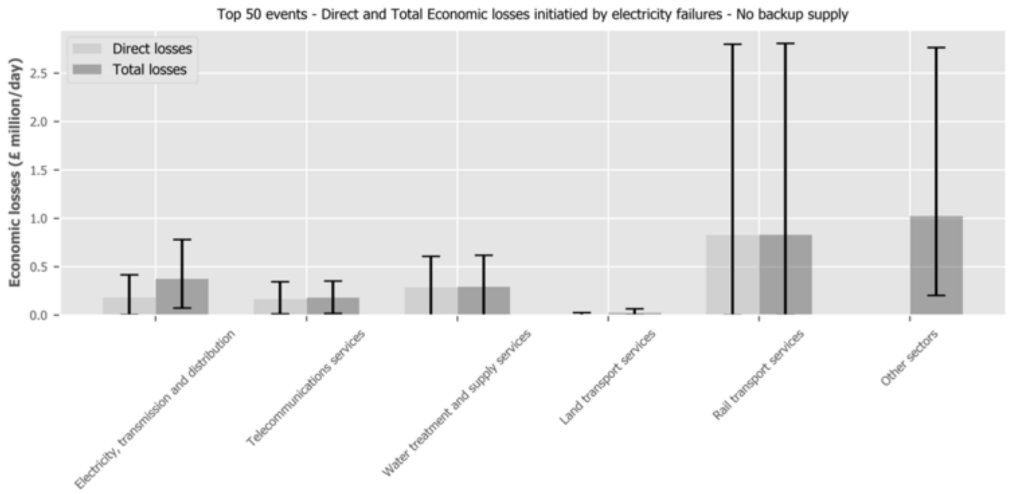


Figure 9. Mean value with 95% CI estimates of direct and total macroeconomic losses across top 50 user disrupted events initiated by electricity failures.

The analysis also explored the benefits of increasing resilience through various resilience enhancing options (explained earlier). Overall, the systemic analysis of the 50 worst-case electricity-initiated disruptive events, showed that when resilience measures are used (i.e. increasing network redundancies with two (2C) and thee (3C) connections) disruptions from electricity networks were reduced by about 70%, telecoms by 91%-95%, water and road disruptions by at least 90% and at most 100%, and railways 82%-93%. A backup (B) supply options was also modelled and found to be most effective for roads where on average disruptions are reduced by about 40%, from the baseline and for other networks the gains were between 10%-23%. Importantly, this demonstrated that there is value in addressing disruptions within the first 10-24 hours, when most of the backup supply prevents further failure cascades. Similar findings were found for resilience options applied to failure events initiated in the telecoms sector. However, the authors did not report on the costs of such resilience options.

Pant et al. (2020) also did some future modelling (baseline, not with climate). Assuming 1.9% GDP compounded growth rate until 2050 and two future electricity scenarios (one with high hydrogen and high electricity for heating), the analysis estimated that the worst-case economic output losses in the future baseline case would be as high as £14 million/day and mostly economic losses would be 1.9 – 2 times current baseline loss levels. Applying resilience enhancing options to the future networks showed similar gains in terms of reduced disruptions and knock-on effects across sectors.

Thacker et al. (2018[clxviii]) present a national-scale analysis for investment in flood protection measures of major electricity substations in England and Wales (107 assets at risk of flooding in total). The study looked into the direct and indirect economic losses that could occur due to the failure of major electricity assets within England and Wales. Based on the authors' calculations, the two sectors that are most affected directly (direct losses) are the telecommunication (£100 million median estimate, up to £600 million, 2009 prices) and electricity sectors (£50 million median estimate, up to over £300 million, 2009 prices); the smallest direct losses occur due to disruptions of airline passengers (£5 million). The largest indirect sector impacts correspond to the business services and real estate sectors (~£30 million median estimate, up to £225 million) as well as the mining sector (~£20 million, median estimate and up to £125 million) (not shown in figure). This emerges due to the large role that these sectors play in the national economy and their strong reliance on infrastructure, for example, the service sectors' dependency on the telecommunications sector and electricity sector. The analysis also includes consideration of the net present value of different adaptation measures. In particular, the authors calculated the NPV for the three different adaptation measures at 2060 (45 years asset life from implementation in 2015). The results show that for all 107 assets at risk of flood, the installation of a floodwall to protect against failure-related losses results in a positive NPV, making the option favourable for investment; only four substation assets show a positive NPV for the substation raise option, and no assets show a positive NPV for the substation relocation option. The authors concluded that investment in high-cost adaptation options such as raising the substations and relocating the substation are cost-beneficial in only a limited number of cases, and investment in such options may become more attractive when an asset is approaching the end of its life (Thacker et al. 2018).

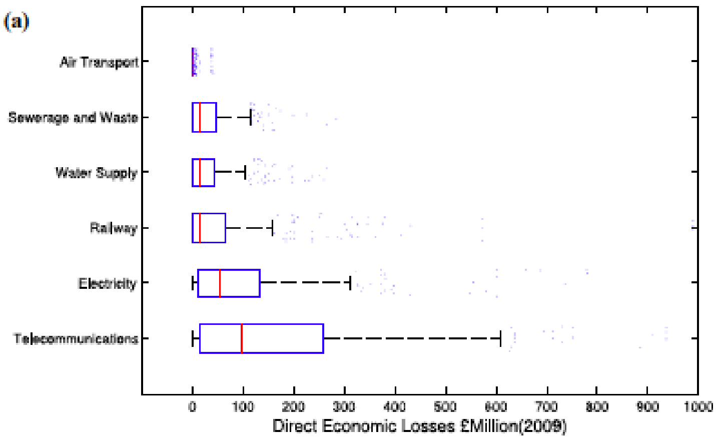


Figure 10. Direct economic losses that can occur due to the failure of major electricity assets within England and Wales (Thacker et al. 2018).

Koks et al. (2019[clxix]) used geospatial information on the location of electricity infrastructure assets and local industrial areas and employed a multiregional supply-use model of the UK economy to trace the impacts of floods of different return intervals across 37 subnational regions of the UK. The authors used the loss in labour productivity (temporary reduced employment) as the proxy for business disruption. The authors calculate system-wide impacts that arise due to the failure of individual assets. For this study, they identified assets exposed to risk of flooding with different annual return periods (1/20, 1/75, 1/100, 1/200, 1/1000). Although the macroeconomic impacts are estimated for the whole of the UK, the actual direct flood impacts and infrastructure failure (and, consequently, the estimation of the business disruption) are focused on five substations in the southeast of England.

When looking at the macroeconomic impact for the UK, it found commercial and public services are most affected, in case of flooding only and for systemic disruption. There is a sharp increase in the total amount of commercial services affected between a 1/75 and a 1/100 flood, i.e. disruption increases significantly with a larger flood event. The results show up to a 300% increase in total economic losses when power outages are included in the risk assessment, compared to analysis that just includes the economic impacts of business interruption due to flooded business premises (Koks et al.,2019). The figure shows the ranked daily total output losses for all failure combinations from the smallest (most left bar) to the largest (most right bar) losses. The left panel (1/1000 flood only) and the right panel (systemic disruption) show a similar ranking, but with up to a factor 3 difference in the size of the daily total output losses. The authors estimated that the total economic loss resulting from failure of five substations (worst case scenario) to be around £27 million per day.

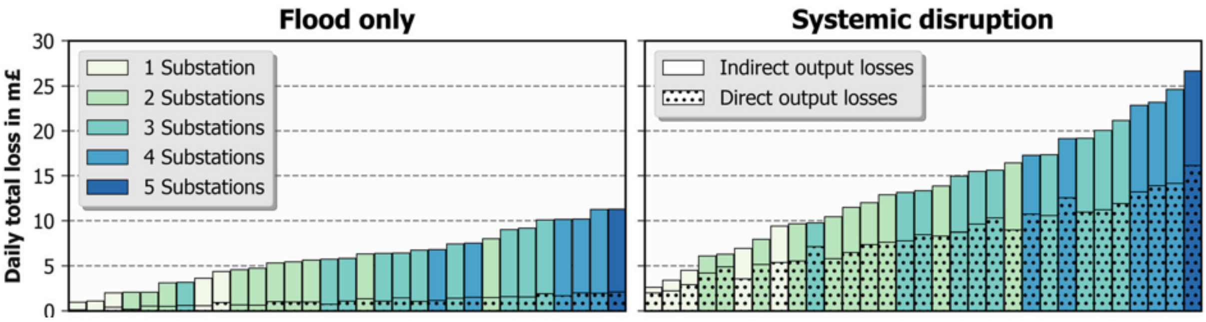


Figure 11 Total daily output losses for the United Kingdom for 31 failure combinations.

The left panel shows the impacts due to a flood with a return period of 1/1000. The right panel shows the impacts due to a flood with a return period of 1/1000 and a failure of the electricity substation at the same time (Source: Koks et al. 2019).

Koks et al. (2019) report that the high multiplier effects in their study, which are higher than many other studies, are because most of the existing estimates do not account for the macroeconomic impacts and are generally underestimating indirect impacts.

The CCRA3 interacting risks project (WSP, 2020[clxx]) considered the consequences of impacts due to climate changes on individual parts of the infrastructure network, for present day, 2050s and 2080s for 2°C and 4°C temperature increases (global, relative to pre-industrial) scaled with macroeconomic growth (GDP and population growth projections). This scored current cascading risks as high (£hundreds of million/year). Using a Bayesian Belief Network system, network (or systems) maps representing interactions within and between sectors were developed. The projections for both the 2050s and the 2080s anticipate a small change in the overall distribution of magnitude scores, with 7 interactions with a high impact magnitude score (unchanged), 16 scored as medium (up from 13) and 3 as low impact (down from 6), as compared to current. They ranked the magnitude for 2 and 4ºC scenarios in the 2050s and 2080s as very high (£billions/year).

The project did identify those effects with greatest number of upstream connections (and so the greatest potential for cascading failures throughout the infrastructure system and wider economy). In terms of infrastructure, power supply interruption had the highest number of connections (15, with 11 being in the infrastructure sector and 4 in the built environment), followed by IT and communications disruption (10, with 7 in the infrastructure sector and 3 in the built environment) and transport infrastructure/hub flooding (7, with 4 in the infrastructure sector and 3 in the built environment). Looking at impacts with large numbers of downstream connections (i.e. can be affected from a number of different sources), those that are affected most by the infrastructure sector are travel and freight delays (13 connections with the infrastructure sector), water supply interruptions (9 connections), transport accidents, power supply interruptions, transport infrastructure damage and sewage flooding (all with 5 connections).

In terms of the pathways with the highest risk level, of relevance to infrastructure, it identified the impact of a heatwave on building occupants (leading to productivity loss); power and water demand increase; and transport overheating, especially railways, leading to transport delays. It also identified the indirect impact of cascades from power and IT and communications disruptions affecting water and transport infrastructure (e.g. signalling). The study estimated the level of risk in terms of the total expected utility, calculated by the sum down an impact chain of each of the impact nodes multiplied by the event probability, multiplied by a weighting factor to take account of the relative value of each impact unit[7]. The increase in overall risk for a 2050 4°C scenario compared to the baseline was a multiple of 5.7 with no scaling for macro-economic impact and a multiple of 6.6 if the macroeconomic impact projections were included.

Table 19 Change in overall level of risk (expected utility) for each emissions scenario and time period. Source WSP, 2020. Note this includes all interacting risks, not just infrastructure related.

	Combined models		Combined models	
	Overall level of risk		Change factor from baseline	
Scenario	Unscaled	Scaled	Unscaled	Scaled
Baseline	345	345		
2050 2°C	1967	2274	5.7	6.6
2050 4°C	1967	2274	5.7	6.6
2080 2°C	3707	5527	10.7	16.0
2080 4°C	4278	6449	12.4	18.7

Note: This table shows the expected value utility of all the Impact nodes in Model 1 and Model 2 combined, summed using the weighting factors for different types of impact, and scaled for population growth or GDP growth by 2050 and 2080.

The impact of cascading risks also feed through to businesses (see Chapter 6). ITIC (2017[clxxi]) undertook a global study on 800 organisations (Reliability and Hourly Cost of Downtime Trends Survey) and report that nearly all organisations reported a single hour of downtime cost over $100,000 and one third over $1 million.

Valuation summary

There are clearly high economic costs that are associated with individual large-scale events, in terms of the major cascading risks (indirect and macro-economic). These individual events are reported at £tens of millions. The question is over how regularly these occur, and the degree to which very large-scale events might occur in the future under climate change. This is more difficult to assess, as there is not a systematic analysis of the economic costs, expressed in annualised damages, nor analysis of future increases in extremes and knock-on effects on cascading risks. The CCRA3 research project (WSP, 2020) investigated and ranked the current risk as high, and future risks as very high (although this includes all cascading risks not just infrastructure). These estimates are used here but it is highlighted there is some potential double counting with other risks and chapters.

Table 20 Valuation of I1. Risks to infrastructure networks from cascading failures.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	High	Very high	Very high	Very high	Very high	
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

7 The dependency model calculates the overall level of risk (expected utility) along each pathway so in order to do this the model needs to assign a weighting factor to take account of the relative value of each impact unit. This weighting factor is used to create equivalents between differently dimensioned parameters on the impact magnitude framework (e.g. pounds or people or hectares affected). For example, in the model, £10m cost is equivalent in utility value to a 1% change in natural capital assets so the weighting factor for % change in natural capital assets is 10 and the weighting factor for cost is 1 (WSP, 2020).

Adaptation
There is some evidence on the potential costs and benefits of adaptation for infrastructure investment (OECD, 2015[clxxii]) and in general positive benefit-to-cost ratios are reported for making infrastructure resilient (GCA, 2019[clxxiii]). However, there is little evidence on the economic benefits for addressing cascading risks or moving to a systems-based approach. The studies that do exist tend to assess the additional benefits in considering indirect costs from adaptation (rather than just the avoided costs of damage to the infrastructure asset and operation itself), e.g. Thacker et al. (2018) for electricity substations, and Pant et al. (2020) for multiple networks (above). The consideration of indirect risks increases benefit streams and thus leads to higher economic benefits (and NPVs/BCR ratios). Evidence from other countries highlights that a systems-approach can also highlight the key vulnerability pinch points in networks, and thus help to direct adaptation, e.g. over-designing some key nodes or elements of the network.

I2. Risks to infrastructure services from river, surface water and groundwater flooding

The CCRA3 Technical Report (Chapter 4) identifies flooding as a perennial risk to UK infrastructure. The latest research indicates that all infrastructure continues to face an increased risk from surface water flooding. In particular, the report identifies that railways look increasingly exposed to fluvial flooding, though due to adaptation, the risk of fluvial flooding appears to be reducing for energy.

Valuation
The Environment Agency's Long-term Investment Scenarios show that over 40% of transport and utilities infrastructure are in areas at current risk of flooding, either directly or due to dependence on other sectors (Environment Agency, 2019[clxxiv]). The costs of the 2007 floods were estimated by the EA (2010[clxxv]) to have costed about £3.2 billion in total (2007 prices), within a possible range of between £2.5 billion and £3.8 billion. Communications, roads (including costs incurred by Local Government Authorities), rail, and telecom accounted for £227 million (best estimate) or 7% of the total costs. The EA[clxxvi] estimated the costs resulting from the winter floods in England following Storms Desmond, Eva and Frank at £1.6 billion, of which rail suffered economic costs of £121million (best estimate) (2015 prices).

There are also a series of studies that report on the direct (and sometimes indirect) impacts of flooding on infrastructure, mostly notably to transport and electricity. For example, the National Infrastructure Commission (NIC, 2020[clxxvii]) identified a number of weather-related events, including cases where flooding had affected electricity substations leading to power outages and road / rail closures.

In the UK, Sayers et al (2020[clxxviii]) for CCRA3 estimated a significant increase in exposure of infrastructure of both Category A (including water treatment, energy and communication infrastructure sites) and Category B (including railway stations, landfill sites, hospitals and blue light service stations, care homes, GP surgeries, and schools) across the UK under future climate scenarios for a 2° and 4°C pathway. However, this was largely based on the current stock of infrastructure, and does not include new infrastructure development, and thus is an underestimate. It reports infrastructure assets currently exposed to a 1:75 or greater risk, with clean water (487 sites river and 147 sites surface water), wastewater (747/601) active landfill sites (5/1), railway stations (596/82), lengths of rail network (3,544km/1,145km), power stations (178/67) and substations (575/234). The figures demonstrate the potential exposure across the infrastructure sector, but excludes ports, airports and digital infrastructure assets such as data centres and telephone exchanges. However, the report does not quantify the expected annual damage. The analysis of future risks in Sayers et al. (2020) finds that infrastructure assets across the four countries will face increased exposure to surface water risk. In some scenarios, a potential doubling of risk in a 4°C world is projected, namely for power stations, electricity substations in England and railways in England, Wales and Northern Ireland.

Forzieri et al. (2018[clxxix]) assessed critical infrastructure in Europe and investigated how single and multi-hazard events could damage energy, transport, industrial, and social critical infrastructures, and how this would change with climate change in the 2050s and 2080s. They estimated the expected annual damage (EAD) for seven hazards (heat and cold waves, river and coastal floods, droughts, wildfires, and windstorms) for three future time periods under the A1B emission scenarios (a medium warming scenario, similar to RCP4.5), expressed as a proportion of the gross fixed capital formation at risk (GFCF, a measure of the annual investments in fixed assets). They report that these damages rise progressively from 0.12% at present to 1.37% by the end of this century for the whole of Europe, although there were lower damages in the UK. For the UK, damage was estimated to raise from 0.14% (EAD in 2020) to 0.37% (EAD in 2080) of GFCF. The authors also estimated capital and operation and maintenance (O&M) costs of adaptation (including for the UK). Note that the analysis assumes independent hazards and static vulnerability; and interdependencies, cascading effects, and the risk of failures were not explicitly modelled. The authors derived indicative costs of adaptation (the additional investments needed to climate-proof infrastructures in different regions) by using a literature-based average benefit-to-cost ratio (BCR) value of 2.5, and combining it with the projected benefits. These were then expressed as a proportion of GDP. Furthermore, it assumed that capital costs reflect 30% of the total adaptation cost over its lifetime and that they are incurred now, whereas O&M costs (the remaining 70% of costs) are spread equally in time. Estimates of adaptation costs indicate that for the UK, costs to be incurred now would equal €575 million (capital costs) plus €44.7 annual O&M costs. This, however, would make infrastructures resilient to climate only up to 2040. The investments for adaptation required to face changes in climate in the medium term (up to 2070) are estimated by the authors to amount to an upfront capital cost of €1.6 billion (0.5% of GFCF), and annual O&M costs of €61 million. To make infrastructures climate resilient up to the end of the century, capital costs in the UK could be ~€4bn (1.4% GFCG) and O&M annual O&M costs could reach €103 million. These findings are shown below along with the EU+ figures (i.e. EU28 plus Switzerland, Norway, and Iceland).

Table 21. Expected annual damage (EAD) and cost of adaptation (in 2010 constant euro prices or percentage of 2010 GFCF) for multi-hazard multi-sector analysis. (Forzieri et al. 2018)

Country	EAD (€ million)				EAD (% of GFCF)				Capital cost (€ million)			Capital cost (% of GFCF)			Annual O&M cost (€ million)		
	2000s	2020s	2050s	2080s	2000s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
UK	403	563	679	1,076	0.14	0.19	0.23	0.37	575	1,566	3,988	0.20	0.54	1.37	44.7	61	103
EU+	3,410	10,304	20,621	37,632	0.12	0.38	0.75	1.37	24,820	86,778	209,977	0.90	3.16	7.65	1,930	3,375	5,444

Transport

The risks of climate change for the transport sector primarily arise from extreme events, such as flooding, heat waves, droughts and storms. As well as direct damage costs to infrastructure, these extremes have economic costs from passenger and freight transport disruption (affecting travel time) and can also affect the likelihood and severity of accidents. There are also wider indirect effects from transport disruption, affecting the supply of goods and services, which can be significant for major events. There is well documented information on the costs of previous flood events. The estimated total costs relating to delays and disruption to road users during the 2007 floods was approximately £100 million (Environment Agency, 2010[clxxx]) and also led to an estimated £25.6 million in rail user delays and a further £10.5 million for rail infrastructure costs. More recently, estimates of flood related costs have been compiled for previous major flood years (Environment Agency, 2018[clxxxi]). This indicates transport related costs of several hundred million.

Table 22 Comparison of economic costs by flood event by impact category (2015 prices). Source EA, 2018.

	2007 (summer floods) (£ million)	2013 to 2014 (winter floods) (£ million)	2015 to 2016 (winter floods) (£ million)
Utilities (energy and water)	£398	£30	£104
Transport (roads, rail, air, ports)	£310	£295	£341
Total (all)	**£3.9 billion**	**£1.3 billion**	**£1.6 billion**

There are also data collected on service costs delays by the Rail sector (as part of the schedule 8 costs), which break down costs by weather events, including the costs of service disruption (Network

Rail, 2017[clxxxii]). This reported that between 2006 and 2016 flooding caused an annual average of approximately £15 million in Schedule 8 compensation payments (this includes river, surface, groundwater and coastal flooding).

There are a number of projects which have tried to quantify the current costs of floods and weather-related events on transport, and estimate future damages under climate change. Ideally this analysis would use the traditional transport appraisal guidance (DFT, 2019) to look at the costs of physical damage (repair and restoration) and also the costs of time delays (using the value of time). However, the latter requires detailed modelling analysis.

The analysis in CCRA1 (Thornes et al., 2011) estimated these risks as being low currently, when expressed in annual terms, and only medium in the future time periods (£10 – 99 million/year).

The WEATHER project estimated that the total costs from extreme weather events are currently €2.5 billion/year in Europe (1998-2010). These are dominated by road transport (€1.8 billion/year 72%), followed by air (€0.4 bn/year 14%) and rail (€0.3 bn/year 12%) (Enei et al., 2011[clxxxiii]: Doll et al., 2014[clxxxiv]). For road transport, the costs from heat stress and flooding are large, but are offset by a large reduction in winter maintenance costs, thus the net average road transport costs will only raise by 7%. For the rail sector, heat stress and heavy rainfall were estimated to increase costs by 72%. The impacts on air transport were considered to be very uncertain because they result from extreme wind and fog, but are estimated to increase by 38%. For the British Isles (UK and Ireland), Przyluski, et al. (2012[clxxxv]) for the WEATHER project estimated the average infrastructure damage cost (2000-2010) for road transport (including infrastructure assets and operation costs, fleet assets and operation costs and users time (delays) and safety related costs) at 0.17 € / 1000 pkm (passenger-kilometre) – below the average of 0.29 across Europe, and one of the lowest of the EU regions. Average cost for rail transport was estimated to be higher, or 0.52 € / 1000 pkm – close to the EU average of 0.57; and for air transport was estimated to be €0.51/1000 pkm (below the EUR29 average of 0.66). Across all transport infrastructures damage costs (total damage and weather-inflicted system operating and user costs) due to climate change were estimated to be approximately £0.55 billion, £0.65 billion and £1 billion/year for the 2020s, 2050s and 2080s respectively.

Projections of changes in 2010-2050 are reported below. For the EUR 29, with a projected increase in transport activities this implies a rise of average damage costs by 5% (road), 39% (rail), and 20% (aviation) due to weather extremes across Europe. Most hit are rail services in France and the UK. For the UK and Ireland (BI in the table), the rail sector is projected to be hit the hardest, with train operators and passengers bearing the highest cost increases (75% and 76% respectively). The table shows that thanks to climate change there will also be winners. For the British Isles, these are road users (-13% costs), and aviation infrastructure assets owners (-21% costs).

Table 23. Summary of forecast results for total transport sector costs due to weather extremes 2010 to 2050 (Przyluski, et al., 2012).

Sector	AL	BI	EA	FR	IP	MD	ME	SC	EUR29
Road	-5%	3%	5%	54%	-17%	-13%	-21%	12%	5%
Infrastructure	-14%	9%	-1%	71%	-19%	-8%	-7%	13%	11%
Services	22%	30%	17%	7%	-16%	-20%	-31%	8%	-3%
Users	7%	-13%	13%	-6%	-4%	-24%	-28%	12%	-7%
Rail	41%	58%	25%	116%	-16%	13%	33%	52%	39%
Infrastructure	21%	24%	6%	106%	-28%	-1%	18%	16%	15%
Services	50%	75%	40%	132%	-15%	28%	43%	52%	50%
Users	49%	76%	39%	83%	-14%	28%	38%	55%	52%
Aviation	12%	26%	6%	31%	28%	36%	9%	8%	20%
Infrastructure	-19%	-21%	-15%	0%	0%	-34%	-21%	-19%	-20%
Services	13%	27%	8%	31%	30%	35%	10%	9%	22%
Users	14%	27%	7%	33%	20%	37%	11%	10%	21%

The EWENT project also estimated current and future weather-related costs for transport. It estimated current costs for all modes and all cost items at more than €15 billion/year for Europe (2010). This is higher than the WEATHER project due to a broader classification of weather events, inclusion of operation and logistical costs, and higher accident levels and thus costs. Climate change is estimated to have different impacts across transport modalities (Nokkala et al., 2012[clxxxvi]). The study found that there is an apparent trend in declining accident costs, also because the winters are getting shorter and warmer in the Northern hemisphere. Icy and slippery roads raise the accident risk up to 2–3 times higher than on dry roads. The winter maintenance operations costs were also expected to decrease throughout Northern Europe (Nokkala et al. 2012).

The PESETA II study (Ciscar et al., 2014[clxxxvii]) considered impacts on the road and rail network in Europe, estimating the total damages to transport infrastructure due to extreme precipitation at €930 million/year by the end of century under an A1B scenario (around a 50% increase from the control period (1961-1990) estimate of €629 million/year) and €770 million/year under a 2°C scenario (23% increase relative to the control period estimate. The table shows estimates for a medium-high emission scenario without mitigation (A1B scenario, similar to RCP4.5) and a scenario consistent with the EU 2°C climate goal. More specific estimates also exist for road transport. The future costs are driven by future socio-economic assumptions, i.e. transport patterns and demand. The values for the UK (and Ireland) are shown as part of the results below.

Table 24 Additional flood-induced damages to road infrastructure for the period 2070-2100 million Euro/year.

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	629	130	59	209	109	122
Medium scenario (A1B)	932	210	89	356	156	121
change (%)	48	61	52	70	44	-1
2°C	773	210	90	218	152	102
change (%)	23	62	53	4	40	-16

Bubeck et al. (2019[clxxxviii]) assessed damage to railway infrastructure only, which already contributes to 10.8%-13.8% of overall flood losses. This study reports that for the UK, the expected annual damage is between €34 and €38 million. However, expected damage is projected to increase under future climate scenarios. They find that costs to the UK under 2°C and 3°C (based on the time periods when the climate model exceeded each threshold, i.e. global warming levels) are projected to be about on average £0.06 billion and £0.1 billion per annum (expected annual damage), respectively.

The COACCH study (Lincke et al., 2020[clxxxix]) assessed damage to road infrastructures due to river flooding with climate change. Road damage only contributes a small percentage (2.3 %) to the total river flood damage observed in the European Union (€0.205 billion of €8.8 billion annually). Looking at climate alone, irrespective of socio-economic development (SSPs), it found a very strong increase in flood risk by the 2080s, especially for more extreme scenarios (RCP8.5). However, the values are very sensitive to the combination of global climate models and regional circulation models. Without adaptation, the EAD increases for Europe by 165% to €537 million per year by the 2080s under RCP4.5, and the increase is 365% to €825 million per year by under RCP8.5. However, when socio-economic changes are included (SSP2), for RCP4.5, the median flood risk will increase from €158 million/year in the COACCH baseline (1996), to €494 million (2031), €954 million (2056) and €1,469 million (2086). In RCP8.5, this increase is larger, from a baseline of €162 million (1996) to €563 million (2031), €1,147 million (2056) and €2,286 million (2086). For RCP8.5, this is a change by a factor of 7.1 (2056) and 14.1 (2086) respectively. The analysis looked at the relative increase in damage under climate change, for RCP 4.5, SSP2, without adaptation. The EAD across Europe, including for the UK, are shown below. For LISFLOOD-OSdaMage, the factor change in damage is 2.5; 4.5 and 7.9 for 2031, 2056 and 2086 respectively. For GLOFRIS, the factor change is 1.7, 3.4 and 7.9 for 2030, 2050 and 2080 respectively. The analysis finds that the most important impact of floods on road disruptions is not in the direct damage to the physical assets, but rather in the travel delay costs and indirect damage to trade flows.

There is also an emerging focus on concentrating adaptation investments on the vulnerability hot-spots of networks, i.e. to identify the points of the system where greater resilience would be most cost-effective (as part of network level analysis rather than for individual assets). To date, this has mostly focused on flooding (Oh et al., 2020).

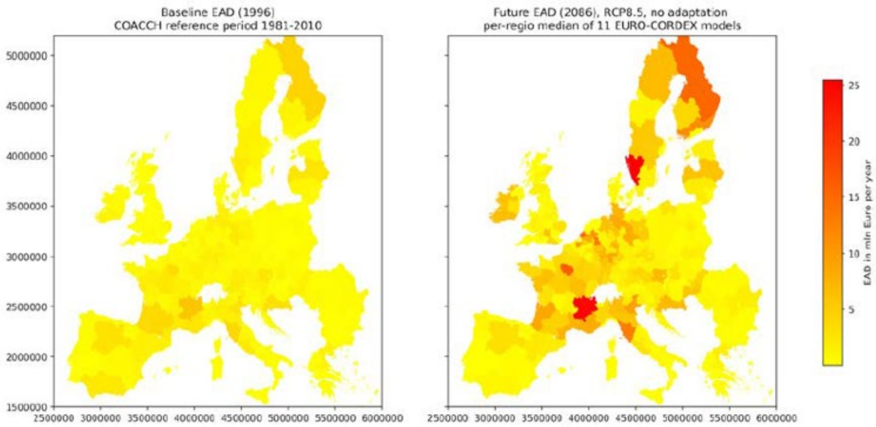


Figure 12 EAD to road infrastructure in 1996 and 2080s, aggregated on NUTS-2 level. Source COACCH (Lincke et al., 2020).

Electricity

There are a number of studies that look at the impacts of flooding on electricity and outages, and in some cases the subsequent economic impacts on households and businesses.

These outages can be valued using estimates of the Value of Lost Load (VoLL), or the value attributed by consumers for unsupplied energy. This can be estimated by different methods including econometric models and case studies of interruptions, but customer surveys are the most prominent, e.g. willingness-to-pay or to avoid a supply disruption. London Economics (2013[cxc]) used contingent valuation and willingness to accept (WTA) to estimate the weighted average value of lost load (VoLL) for the UK at £16,940/MWh for residential and SMEs (the study looked at a one-hour outage every 12 years). For industrial and commercial (I&C) customers, a variety of GVA/MWh value-at-risk approaches suggested an average VoLL of about £1,400/MWh on average, though different sectors showed a wide range of variation. These are lower (than residential) as these users may have their own generation and back-up equipment, and would be less likely to face constraints for cash and capital outlays, and have better information regarding outage costs. As noted by RAE (2014[cxci]), there are some issues, notably the large disparity between willingness to pay (WTP) and WTA estimates, and the use of one-hour outages every 12 years, which does not necessarily translate into examples across the year, and makes it difficult to put these numbers into context. RAE present estimates of VoLL using an online cost-simulation tool that uses the data from thousands of surveys and valuations in each of the EU-27 countries to estimate the overall costs of a supply interruption for a specified area, time and duration. Estimates are derived from the total cost to the economy, divided by the total energy unserved during the interruption. One limitation of the method used – as explained by the authors – is that data from individual consumers and businesses are aggregated up to the whole economy, and then extrapolated back down to generate VoLL per MWh. They indicate average VoLL of ~£6000 for one-hour interruption, and £4000 for 12 hour interruptions. These should be taken as indicative.

Frontier Economics et al. (2013[cxcii]) estimated that – without an increased level of adaptation – by the 2020s, up to 214 GWh of annual generation output could be lost due to flooding (75-year return period). This could rise to an annual output loss of between 30 GWh and 429 GWh per annum by the 2050s, depending on the duration of the outage period and the generation capacity at risk. To estimate the associated costs of such lost output, the study assumed that the shortfall in generation of combined-cycle gas turbine (CCGT) plants would be met by using existing reserves - specifically, open cycle gas- turbine (OCGT) plants were assumed to be used instead of the affected plants. Given that the marginal cost of this type of plant is about 2.8 p/kWh higher than the marginal cost of a gas fired CCGT plant, the incremental (undiscounted) expected average annual cost of flooding was estimated to range between £0.2 and £0.6 million per year in the 2020s, and £0.8 - £12 million per year by the 2050s. The report also investigated the impact of a one-off flood event (as opposed to an average or 'expected' impact, as above), and estimated that the incremental one-off cost of the lost output during a six- month outage period would be approximately between £11.4 and £67.3 million in 2012 prices – though this sits within a wide range of uncertainty (Frontier Economics et al., 2013).

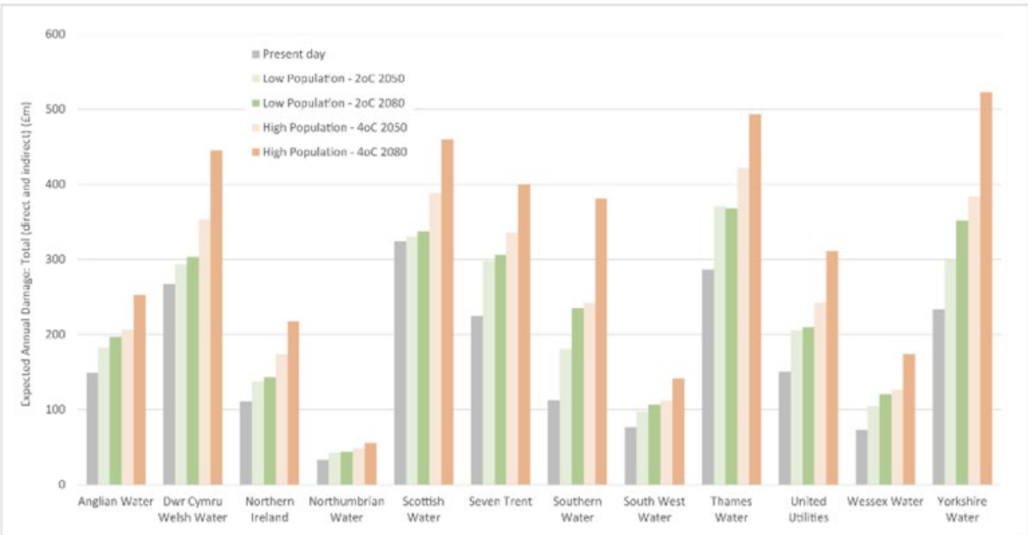
Karagiannis et al. 2019[cxciii] investigated the impacts of flooding on critical infrastructure in Europe, and undertook a case study on electricity interruptions. The analysis modelled a flood episode leading to evacuation of the affected population and a power outage for a 1/10, 1/100 and 1/200 flood scenario. They report that the total economic impact more than doubles between the 1/10 and the 1/100 flood scenarios, and increases by approximately 10% between the 1/100 and the 1/200 flood scenarios. The losses from the disruption of the local economic activity are found to be by far the major contributor to the economic impact of the flood and outage in all three scenarios, consistently amounting to about 99% of the total cost. Of the remaining, the cost of substation damage is 10 times greater than damage to transmission. The significant increase in economic impact for the 1/100 scenario relative to the 1/10 is due to the larger inundation area in the former scenario and from the assumption of a longer duration of the flood and power outage. In other words, the 1/100 flood affects more businesses and for a longer time. However, the authors report that flood scenarios with a low return period yielded the highest level of risk - which is the product of the occurrence probability and the economic losses. In other words, the repeated impact of high probability/low severity floods is likely to have larger consequences than low probability/high severity events.

There is also the study by Koks et al. (2019[cxciv]), reported in risk I1, which looked at the impact of floods on electricity infrastructure assets.

Water

Several recent flood events have led to impacts on water treatment plants and water supply interruptions. Severn Trent Water estimated that the cost of the flooding in 2007 of the Mythe treatment works, which caused loss of supply to 350,000 people, was between £25-35 million (Environment Agency, 2015). Sayers et al. (2020) for CCRA3 estimated that all water company regions will experience an increased risk of flooding, though the increase in risk can be reduced if adaptation measures are taken. It presented EADs for each water company region.

Figure 13 Expected Annual Damage: Total – By Water Company region (no additional adaptation)



Other sectors
There are a very large number of other infrastructure assets and services at potential risk from flooding. The CCRA3 Technical Report highlights potential impacts on disruption to solid waste infrastructure as an example. There are also potential risks to ICT infrastructure. It also highlighted that climate change will affect current flood protection infrastructure.

Valuation Summary

Table 25 Valuation of I2. Risks to infrastructure services from river, surface water and groundwater flooding.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	High	High (possibly very high)	High (possibly very high)	High (possibly very high)	Very high	
Confidence	Medium	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation
There is evidence on the potential costs and benefits of further adaptation. Much of this indicates high economic benefits from investing in flood adaptation for infrastructure (OECD, 2015: GCA, 2019). This is also found in the UK analysis (Sayers et al., 2020). However, some care should be taken in interpreting much of this evidence, as much is based on 'predict and optimise' studies (where future risk levels are known), rather than an analysis taking account of uncertainty (and thus the potential for under or over investment).

More generally, there are a range of low-regret measures that have been identified in this area (Vallejo and Mullan, 2017[cxcv]; Watkiss *et al.,* 2019[cxcvi]), which include:
• Supporting decision-making by providing tools and information,
• Screening climate risks (climate risk management) in public investments,
• Screening climate risks (climate risk management) in private sector investments,
• Enabling infrastructure resilience through policy and regulation,
• Encouraging the disclosure of climate risks/uptake in commercial finance,
• Supporting innovative risk spreading (insurance).

There are also estimates of the economic benefits and costs of some green infrastructure (McVittie *et al.,* 2017[cxcvii]), though these are often site-specific. It is highlighted that there are important governance challenges, as well as opportunity and transaction costs associated with green infrastructure (Watkiss *et al.,* 2019). The benefit to cost ratios of SuDS have been studied (e.g., Ossa-Moreno *et al.,* 2017[cxcviii]) and there are also some economic studies of larger nature-based solutions for flood management, for schemes across Europe[cxcix], and in the UK (EA, 2009[cc]; Frontier et al., 2013[cci]). These show that these schemes can have positive benefit to cost ratios, especially when all ecosystem services are included, but they also vary according to time periods and discount rates considered. There are also studies that report high BCRs for schemes that combine grey and green schemes[ccii], reflecting the fact that NBS may be more appropriate for mitigating more frequent, low level flooding, rather than major extremes.

I3. Risks to infrastructure services from coastal flooding and erosion

The CCRA3 Technical Report reports that coastal flooding and erosion are potential risks to infrastructure and associated services, and hazards will increase with sea level rise. While coastal protection has increased, notable instances of coastal flooding still occur (e.g. in the winter of 2013/14) and have impacted infrastructure along the coast. Significant assets remain in low-lying coastal areas and will be threatened in the event of a defence failure (e.g. overtopping or a breach). Extreme water levels are very likely to increase during the 21st century and beyond, and without further adaptation (e.g. raising flood defences, managed retreat), and the projected increases in extreme water levels are projected to significantly increase coastal flood and erosion risk.

Valuation

There are similar issues with respect to coastal flooding for infrastructure, as well as the added risk of erosion. There have been some high-profile cases where coastal storm surges and erosion have affected infrastructure. The storms at Dawlish on 4 and 14 February 2014 caused a 100m breach in the sea wall, exacerbated by a 25,000 tonne landslip at Teignmouth and a further landslip on 4th March. The railway line, which ran just behind the sea wall, was closed for eight weeks while 300 engineers repaired the line at a cost of £35 million. The cost to the economy in Plymouth alone was estimated at over £600,000 a day[cciii]. Network Rail estimated that the closure of the Dawlish section of track in Devon between February and April 2014 cost the local economy £1.2 billion (written evidence provided to House of Commons, 2018[cciv]).

Dawson et al. (2016[ccv]) assessed projected sea-level rise impacts on the functioning of the Dawlish to Teignmouth stretch of the London to Penzance railway line. The study projected reliability issues due to flooding by 2040, with line restrictions increasing from 10 days per year to 30–40, and maintenance costs tripling or quadrupling (£6.9–£8.7m per year, including over £1m compensation). Dawson et al. (2017[ccvi]) applied a real options analysis (ROA) on a section of coastal rail infrastructure in South-West England that is potentially vulnerable to sea-level rise to examine three adaptation choices: do minimum (baseline), improvement of the current defences (option 1), and a retreat of the line further inland (option 2). The study estimated the option value of delaying adaptation decisions by eight years. Since this is an ex-post analysis, where the benefits and costs existing for both time periods are known, the authors investigated the option value of the new climate information that becomes available in the period between 2002 and 2010 by using UKCIP02 and UKCP09 projections. The results indicate that there it would be economically inefficient to undertake any of the adaptation options to improve the resilience of the region's rail network. The present value costs (PVC) (e.g. capital cost of investment and maintenance costs) overwhelm the benefits of adaptation for all options over the 60 year period. Nonetheless, the authors showed that using different climate information led to different NPV results, and estimated the value of delaying adaptation to be £33 million for option 2, and £166 million for option 1. In other words, the authors were able to show that in this case, as new information has become available, the economic case for building resilience options has changed If the option had been to invest in adaptation in 2002, the impacts and benefits would have been over estimated as the range of uncertainty of sea-level estimates was subsequently narrowed in 2010.

CCC (2018[ccvii]) reports that in England, transport, energy and waste infrastructure and cultural assets are exposed to coastal flooding and erosion. Approximately 7,500 km of road, 520 km of railway line, 205,000 ha of good, very good or excellent agricultural land, and 3,400 ha of potentially toxic historic landfill sites were reported to be at 0.1% or greater risk of coastal flooding in any given year. Power plants, ports, gas terminals and other significant assets are also at risk. However, the report does not estimate the expected annual damages for these assets.

Sayers et al. (2020) also quantified the current number of assets or length of infrastructure exposed to a 1:75 chance of annual coastal flooding for major receptors including clean and wastewater sites, electricity generation sites and transport networks. Notably, 35 power stations were identified as at risk along with 22 clean water facilities and 91 sewage treatment works across the UK. The entire nuclear fleet of power stations is located in the coastal zone, with the Office for Nuclear Regulation expecting nuclear licensees to provide flood protection to a return period of 10,000 years. There are also acute problems on the railway network at key locations across the four nations.

There was a detailed study of the potential risks of climate change to coastal roads, undertaken for Transport Scotland (Milne et al, 2016[ccviii]). This selected a case study site for a section of the A78 that runs along the west coast of Scotland which is low-lying land. The analysis looked at the impacts of a sea level rise increase of 0.2 – 0.39m by 2100 and looked at the direct costs and the additional impacts on travel time. The analysis found a significant increase in the risk of coastal flooding (almost a doubling) under climate change. The damage costs and travel time delays of the benchmark flood event were estimated for a historic event, the 3 January 2014 flood. Using a traffic model, the analysis estimated the costs of this event (including travel time). It then looked at the projected changes in coastal flood events with climate change (from the doubling of risk) and looked at the occurrence of such an event in the future. The annualised results below show the direct damage costs, and then the total costs (including travel delays) with and without future traffic growth. If future traffic growth is included, the user costs rise very significantly, though this is due to the combination of an increased climate signal affecting a very much larger baseline level of traffic.

Table 26 Coastal flooding annual direct (top) and user (bottom) direct economic impacts (2012 prices) for low, medium and high emission scenarios (central estimates). Source Milne et al. 2016.

Event Year	Present		2025			2050			2100	
	(2010-12)	L	M	H	L	M	H	L	M	H
Frequency (events/year)	1.1	1.2	1.2	1.2	1.2	1.3	1.5	1.8	2.2	2.5
Annual cost (£)	33,640	36,698	36,698	36,698	36,698	39,756	45,872	55,047	67,279	76,453

Event Year	Present		2025			2050			2100	
	(2010-12)	L	M	H	L	M	H	L	M	H
Frequency (events/year)	1.1	1.2	1.2	1.2	1.2	1.3	1.5	1.8	2.2	2.5
Annual cost (£): No Traffic Growth	148,816	162,345	162,345	162,345	162,345	175,874	202,931	243,517	297,632	338,218
Annual Cost (£): With Traffic Growth (at ×2.40)	148,816							2,024,980	2,474,975	2,812,472

In Scotland, the National Coastal Change Assessment (Dynamic Coast) estimates that by 2050 at least 1.6 km of railway, 5.2 km of road and 2.4 km of clean water network as well as significant areas of runways, would be affected by coastal erosion (Hansom et al., 2017[ccix]). The CCC also reported (2019[ccx]) that there are assets worth £13.3 billion within 50 metres of the soft coast of which £340 million worth is expected to be threatened by erosion by 2050.

Valuation summary

There is very uncertainty associated with this risk and thus it is included as unknown, but it could be potentially high, especially in later years.

Table 27 Valuation of I3. Risks to infrastructure services from coastal flooding and erosion

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK		Unknown (Possibly high)	Unknown (Possibly high)	Unknown (Possibly high)	Unknown (Possibly high)	
Confidence						

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

In general terms, the literature reports that coastal adaptation is an extremely cost-effective response, significantly reducing residual damage costs down to very low levels (Hinkel et al., 2014[ccxi]) with very high benefit to cost ratios. The National Infrastructure Commission (2018[ccxii]) analysed the investment that would be required to provide a range of resilience standards for coastal flooding. The benefits of achieving a resilient infrastructure sector were estimated as the value of the 'avoided' or 'mitigated' damage and disruption caused by climate-induced events. Similar analysis was undertaken by the Environment Agency (2014[ccxiii]), updated in Environment Agency (2019b), who estimated that the net present value of the optimised long-term investment in flood and coastal erosion risk protection, including the economic damages avoided by making the investment, including the benefits of protecting infrastructure.

I4. Risks to bridges and pipelines from flooding and erosion

The CCRA3 Technical Report reports that there is limited evidence on the risks to bridges and pipelines, with little quantified evidence. Most information is associated with weather events and environmental hazards which underlie the risk (e.g. rainfall, temperature, erosion for pipelines; increased hydrostatic pressure, scour for bridges). Further research is needed to define the links between the forecasts and the actual projected impact at the local, regional and national level.

Valuation

There is limited information on the physical impacts of this risk, which makes quantification more challenging. In terms of valuation for bridges (transport), the approach should ideally consider the costs of the damage (usually the repair cost) but also the impact on travel, captured through analysis of delays and transport user benefits. The latter can be quantified using typical values from DfT appraisal (DFT, 2019) through the value of travel time savings (or in this case, increases in travel time). The same concepts apply to pipelines, in terms of the direct damage plus the loss of benefits (of what is being transported in the pipeline).

There are a set of historical failures of bridges and pipelines from weather extremes which provide some context. For example, the National Infrastructure Commission (NIC, 2020[ccxiv]) identified a number bridges collapsing during the 2015 floods. The costs of repairs for individual assets can be high. The CCRA2 technical report (Chapter 4 – Infrastructure) cites a study (van Leeuwen and Lamb, 2014) that indicates that a flood event in which one or more bridges fail due to high river flows is currently expected to occur once every 2.6 years in the UK.

CCRA1 looked at the potential impacts of bridge scour from climate change (Thornes et al., 2011[ccxv]) but it was not possible to estimate the potential number of bridge failures, therefore the assessment was qualitative. It ranked the risk as low in monetary terms (£1 – 10 million/year). CCRA2 (Dawson et al., 2016[ccxvi]) reported that increased winter precipitation and river flows will increase scour at bridges, potentially increasing the rate of failure to an average of one bridge per year in the UK.

There is some older literature on the costs of adaptation for bridges (road and rail bridges) to address scour risk (Nemry and Demirel, 2012[ccxvii]), which includes estimates for the UK and Ireland. These provide a proxy for damage costs. For the UK and Ireland, annual costs were estimated at €47 million/year in the 2050s. Of these costs, 80% were for road and 20% for rail bridges. This is reported at approximately 2% of current road maintenance costs.

There is also some European analysis. Ciscar et al., (2014[ccxviii]) estimated the costs of protection of river bridges against scour risk would rise over the next decades for about 20% of the river bridge stock because of increasing intensity of peak river discharges. Given the long lifetime of bridges (>100 years) this is important for the current stock. The annual cost of protecting bridges across Europe was estimated at €541 million for the time period 2040-2070 and €383 million for the time period 2070-2100.

HR Wallingford (2014[ccxix]) assessed the future scour vulnerability of bridges in England from increases in winter precipitation and river flows, by modelling the link between flow depth and scour depth. According to their analysis, potentially 1 in every 20 bridges will be at high risk by 2080 (HR Wallingford, 2014).

For the road network, earlier work (Atkins, 2013[ccxx]) looked at the potential risks of climate change on roads for the Highways Agency. This focused more on hot weather, but included bridges. This looked at reduced service life, additional maintenance and associated closures (with travel time delays). The estimated costs for bridges were low (~£13 million in present values over a 60-year period, in the worst-case climate scenario), and significantly lower compared to the equivalent damages for road surfaces (estimated at £64 million).

Bridge tunnels have long lifetimes. Lamb et al. (2019[ccxxi]) considered the economic costs of bridge failures due to scour over the British rail network, including travel time costs, estimating the annual risk (expected annual utility cost to passengers, but excluding freight and speed restrictions when scour damage is suspected) of between £6 million and £60 million. This provides some baseline costs, onto which future climate risks will act.

There is less information on pipelines. The main hazards for pipelines include flooding and heavy rainfall (including saturated ground conditions), snow and ice, increases in temperature, coastal and river erosion, storm events and high winds. The CCRA3 Technical Report (Chapter 4) highlights that there is low evidence on these risks.

The information in the Technical report and above highlights that there is low confidence in the magnitude of this risk, and especially for pipelines. An indicative score of medium has been given, although there is a low confidence in this, and it is plausible that in a 4ºC future, the impact could be high.

Table 28 Valuation of I4. Risks to bridges and pipelines from flooding and erosion.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Medium	Medium	Medium	Medium	Medium	
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

The costs of adapting pipelines and bridges to climate change are very site-specific, and costs vary significantly between adapting the current stock versus new infrastructure. There is some older literature on the costs of adaptation for bridges (road and rail bridges) to address scour risk (Nemry and Demirel, 2012), which includes estimates for the UK and Ireland where annual costs are estimated at €47 million/year in the 2050s. Of these costs, 80% are for road and 20% for rail bridges. This is reported at approximately 2% of current road maintenance costs. The benefits of adaptation – in terms of avoided scour, possible failure, and subsequent repair or reconstruction (and indirect effects include travel time losses) – were not assessed, though the costs of any failures are normally large. The Tomorrow's Railway and Climate Change Adaptation (TRaCCA) programme did look at options for the rail network overall to adapt in the most cost-effective way, with some quick wins suggested, although for scour this focused on better vulnerability information (RSSBa, 2016[ccxxii]). For the road network, Atkins (2013) looked at the potential risks of climate change on road bridges for the Highways Agency (but considered all risks, not just scour). This looked at reduced service life, additional maintenance and associated lane closures, and found the benefits of adaptation were similar to costs for central scenarios (with benefit to cost ratios close to one) but BCRs rose significantly under worst case scenarios.

I5. Risks to transport networks from slope and embankment failure

The CCRA3 Technical Report (Chapter 4) identifies that the increased incidence of high rainfall, combined with preceding periods of desiccation and cracking, are projected to lead to an increase in incidents of slope failure within the transport network. Rainfall is reported as the main trigger of deterioration of the mechanical and hydraulic properties of engineered fill forming infrastructure slopes, especially considering wetting-drying and freeze-thaw cycles. Extreme weather is expected to increase the rate of these deterioration processes; however, the evidence reviewed suggest that these deterioration processes are not yet fully understood.

Valuation

The main driver for slope failure is rainfall. Landslides occurring after periods of intense, heavy rainfall are likely to result from either water loading of the slope, reduction in soil strength, removal of soil particles, or other material changes in the slope. Drier summers may also pose difficulties for earthworks, causing cracking and shrinkage problems in clay soils. The older an earthwork, the more cycles of stress it will have undergone and the more vulnerable to failure it will be. The British Geological Survey (BGS) continuously captures landslide data in the National Landslide Database (NLD). This shows that periods of high rainfall accumulation are associated with an increase in landslide activity. For valuation, the same approach as for the previous risk is considered, captured through analysis of delays and transport user benefits (value of travel time).

However, the lack of detailed projections – and information on physical impacts – makes it quite difficult to estimate the potential monetary impacts. Nevertheless, many of the UK transport slopes and embankments are old and do not offer comparable levels of capability and resilience to modern engineered slopes. There are approximately 9,660 km of embankments in the UK owned by the four main infrastructure owners; Network Rail (5,000 km), Highways England (Formerly Highways Agency; 3,500 km), British Waterways (1,100 km) and London Underground Ltd. (60 km).

Railway cuttings have been identified as a major source of risk. Network Rail (NR) alone manages a portfolio of over 190,000 earthwork assets (embankments and cuttings). CCRA2 highlighted that there were, on average, 67 earthwork failures a year across the rail network between 2003/04 and 2013/14. It also reported increased incidences of natural and engineering slope failure affecting the road and rail network in the winters of 2012/2013 and 2013/2014. Weather-related delays (schedule 8 costs) are reported by Network Rail (2017[ccxxiii]) - subsidence events occur less frequently but create a high cost per incident. There have also been several high-impact examples of failure, notably the landslide (that followed severe rain) in Stonehaven (Scotland) in 2020, where a passenger train hit a landslip and derailed, causing three casualties. In 2009-2014 (control period 4 – CP4), Network Rail's investment in earthworks and drainage exceeded £100 million per annum (on average) (~£700 million in total), and in 2019-2024 (CP6) it has nearly doubled reaching £ 1.274bn (Haines, 2020[ccxxiv]). For CP6, NR identified in 2018 the potential to use £185m as a risk fund, also to respond extreme weather events. In addition, included in NR's plans, are £33m to increase remote monitoring and sensing, improve weather services monitoring and diagnostics for earthworks and drainage, together with £31m on research and development specific to earthworks, drainage and resilience.

There is one study that investigates the costs of landslips on the rail network and projects future costs from climate change (TRL, 2013[ccxxv]), looking at a number of case study sites. This provides some costs for current events (in terms of restoration costs, indicating £tens of millions).

Landslides also affect the road network (e.g. SG, 2005[ccxxvi]), and these can have very large costs from the combination of direct damage and emergency response, remediation costs and travel delays (immediately after, and for long periods afterwards). Older data indicate that repair of highway embankment and cutting slopes cost approximately £20 million per annum in the UK in 2010 (Arup, 2010[ccxxvii]). The additional costs of delay and the costs of highway closure could be of the order of £5,000 to £10,000 per hour per lane of motorway (Lords Hansard, 2007[ccxxviii]).

Studies find that these risks are projected to increase with climate change (AECOM, 2017[ccxxix]), though information is generally in the form of levels of vulnerability, rather than estimated impacts or economic costs. Wilks et al. (2015[ccxxx]) argue that while rising temperatures (drier summers) and increasing precipitation (wetter winters) are likely to lead to slope failures along transport infrastructure within the UK, but they find a wide range of results depending on the climate models. Postance et al. (2017[ccxxxi]) used landslide susceptibility data to generate a set of possible landslide-prone road segments in the UK. A total of 152 road segments were identified as susceptible to landslide activity, representing 34% of the strategic road network (i.e. 1,500 of 4,300 km), which could cause indirect economic losses exceeding £35,000 for each day of closure. The authors highlight that previous estimates for historic landslide events might be significant underestimates. For example, their model estimated losses for the 2007 A83 landslide of £80,000 day, totalling £1.2 million over a 15-day closure, approximately 60% greater than previous estimates.

It is also highlighted that there are plans to scale up improvement and preventative measures in both the road and rail networks to address these risks, and plans indicate large increases in expenditure (e.g. Highways England, 2019[ccxxxii]: Network Rail, 2017[ccxxxiii]).

The lack of information makes this risk difficult to assess, and this is further complicated by the need to consider (and thus estimate) the probability of annual damages. It is assessed as a medium to high risk, but there is low confidence with this score.

Table 29 Valuation of I5. Risks to transport networks from slope and embankment failure.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Medium	Medium-high	Medium-high	Medium-high	High	
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

<u>Adaptation</u>

There are some clear low-regret options for addressing these risks. For railways, inspection and maintenance are key activities to monitor slope and embankment failure risks in advance, at a relatively low cost (RSSB, 2016[ccxxxiv]). Currently, routes use a drainage decision support tool and data collected from drainage inspections, surveys and assessments, with drainage assets currently required to be inspected at least every five years (Haines, 2020[ccxxxv]). A low-regret option would be to increase inspection frequency (especially for higher risk areas).

Drainage is also key for the stability and resilience of earthworks. There are obvious low-regret and easily implementable options for enhanced maintenance of drainage systems for addressing surface and groundwater water away from roads and railways. The costs of increasing drainage capacity in new road infrastructure also appears to be low regret, adding only a small percentage to the overall construction costs. For new builds, there are also options for improving monitoring around complex systems such as embankments; Tang et al. (2018[ccxxxvi]) recommend remote sensing tools and report that new engineered slopes are an opportunity to design intelligent monitoring systems in a cost-efficient way, e.g. by installing systems during construction rather than retrofitting them later.

There is mixed evidence about the effectiveness of specific interventions such as vegetation management. This can help manage soil moisture fluctuations in the near-surface zone (Tang et al.

2018), and there is evidence that mature trees have positive effects on embankment slopes (Smethurst et al., 2015[ccxxxvii]). However, Network Rail reported that the removal of trees is not necessarily the cause of landslips; during summer they may cause the earthworks to dry out, and they can pose additional risks during windstorms. On the contrary, there is an increased incidence of trains running into fallen trees; vegetation management has a role to play in mitigating climate risk of earthworks, but it needs trade-off between benefits and risks (e.g. at the toe of an embankment).

However, there is high heterogeneity with site and location (Glendinning et al, 2014[ccxxxviii]) which means adaptation is context specific (and thus so are benefits and costs).

I6. Risks to hydroelectric generation from low or high river flows

The CCRA3 evidence review identifies that hydroelectric power is vulnerable to low flows and high (peak) river flows, but may also benefit from higher average flows. High flows can also be an issue for debris and sediment. Low flows reduce power output; whereas extreme high river flows can damage the generation equipment and associated infrastructure, including dam structures, spillways, etc. In general, changes in flows can lead to potential losses in revenue, that can be £tens of millions, as happened during the reduced rainfall in 2018. The future projections of impacts on hydroelectric generation are somewhat uncertain and include a potential mix of positive and negative effects. In terms of generation, the evidence indicates generation potentially increasing in the winter and decreasing in the summer, although the high uncertainty around future rainfall projections in the UK need to be considered. The potential effects of these changes also depend on the project type, and the difference in risks and opportunities for storage versus run-of-river plants. Storage projects have more ability to capture increased winter flows and balance low summer flow. The overall magnitude was considered high, because of the general UKCP18 projection for dryer summers. There is less information on peak flows and potential damage.

<u>Valuation</u>
Hydropower generation is a climate sensitive activity, and will be affected by future climate change. Changes in the hydrological regime can lead to potentially large financial costs to operators of individual plants, from low flows, high floods and sediment load. These impacts can reduce revenue and potentially incur penalties, and in cases where hydroelectricity is important in national electricity supply, it can lead to high economic costs at the system (national) level.

There are quite large year-to-year variations in hydro-electricity generation, which are influenced by climate. As highlighted in the Technical Report, there were lower flows in 2018 which reduced hydroelectricity output, and a reduction of 500GWh in part was attributed to lower rainfall (BEIS, 2019[ccxxxix]), which would equate to approximately £29m of lost revenue based on wholesale contracts (Ofgem, 2020[ccxl]). However, such dry periods do not happen every year, and thus these costs need to be annualised. The long-term average effects will be lower, and will include positive and negative years, relative to the average.

There are several studies that have looked at how the potential changes in rainfall and river flows from climate change will affect hydroelectric generation at the European level, which includes analysis for the UK. Most studies show a positive effect for Northern Europe and a negative effect for South and Eastern Europe, but the size of the effect varies in studies from almost no effect to changes of 5-10% by the end of the century (Tröltzsch et al., 2018[ccxli]). Again, there are large differences projected between storage and run of river. For example, Després et al. (2020[ccxlii]) considered a number of different climate models and looked at 2°C and 3°C scenarios, identifying possible modest increases (~0.5% and ~2%) in production in the UK, though with a range that included similar % negative values. Similarly, Tobin et al. (2018[ccxliii]) projected a change in power output of 2% for 2°C and 0.5 % for 3°C, again with a range that broadly spanned -2% to +5%. These changes can be investigated using an indicative analysis. Total UK hydroelectricity generation over the last five year (DUKES, 2020[ccxliv]) has averaged 5,786 GWh/year. A change of 2% is therefore equal to £12 million/year, when valued using the long-run variable cost (LRVC) of electricity supply (BEIS, 2019[ccxlv]). However, such scenarios focus very much on the changes in the average rainfall.

The UKCP18 projections generally project drier summers and wetter winters. This might imply larger changes, then from the average. For example, the impact of the dry 2018 summer could become more frequent, reducing generation (although, there might be benefits from wetter winters, at least for storage projects). The potential for system level impacts is small, because hydropower represents only 2% of installed capacity and generation.

There is some potential for additional hydroelectricity capacity in the UK, and this may be incentivised by the Net zero target, although the CCC net zero report (CCC, 2019[ccxlvi]) does not anticipate increases in installed capacity.

There is less information on the potential risks of damage from higher peak flows. There is good evidence that peak flows will increase (Sayers et al., 2020) with climate change, and these increases could be significant for many rivers, especially under higher warming scenarios, notably in Scotland (where a large proportion of hydro is installed). Projects are generally designed to maximum flow levels, especially storage projects, but there are likely to be changes in the frequency of high peak flows and a reduction in the return period of extremes.

The annualised valuation summary is presented below. The current levels are generally low in annualised terms, though could be medium (£tens of millions) in low flow years. Similarly, the projections of changes in hydroelectricity in future years indicates that on average, the net (risks and opportunities) values might be a low or medium score, and could be potentially positive or negative. These estimates do not take into account the potential for higher peak flows and potential damage.

Table 30 Valuation of I6. Risks to hydroelectric generation from low or high river flows

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low in annualised terms but medium in high risk years	Medium (range varies from positive to negative)	Medium (range varies from positive to negative)	Medium range varies from positive to negative)	Medium (range varies from positive to negative)	
Confidence	Medium	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

There is now considerable information on the technical adaptation options available for the hydro-electric generation sector, including sector specific guidance (IHA, 2019[ccxlvii]), albeit primarily focused on new builds. There are also many international studies that look at the costs and benefits of adaptation, for current plants and especially new build (e.g. Nassopoulos *et al.* 2012[ccxlviii]; Cervigni *et al*., 2015[ccxlix]; NRDI, 2016[ccl]).

There are also several studies that look at the potential economic costs of changes in rainfall and river flows, and thus hydroelectric generation at the European level, as described above, but there are large differences between studies (and projections and scenarios) including projections of reductions in output, and differences between storage and run-of-river. Consideration of different studies reveals the considerable uncertainty involved, and thus the need for both low and no-regret options and iterative adaptive management. For new plants (although these are not a major focus for the UK, even under net zero scenarios), decision making under uncertainty is key, and has been applied (see international studies above).

For existing plants there are a set of no-regret options for high flows, notably with weather and climate services, for both extreme events and early warning but also more general reservoir operation optimisation. There are also various engineering options for additional spillways, and measures such as fusegates which can be added, which are generally considered low-regret options for addressing high flow risks. There are more structural options to address changes in flood return period and peak intensity, but these tend to be much more expensive.

The large downside risks for hydropower revenues are from low flows during periods of drought, especially for run-of-the-river plants. Most adaptation studies focus on turbine upgrades (e.g. EBRD, 2015[ccli]) which are more cost-effective than larger structural changes (dam heightening, conveyance structures), although there is usually some degree of trade-off (i.e. lower optimisation but greater flexibility for flow variation). Turbine upgrades also offer some potential to take account of upside risks.

There is greater potential for including all these adaptation measures in the design and construction of new projects, and decision scaling has been quite widely applied to take account of climate risks and plan adaptation at the international level for such assessments (e.g. Ray *et al*., 2015[cclii]; Karki *et al.* 2015[ccliii]), and is incorporated in the IHA guidance (2019). However, there is often a careful balance of costs and benefits of adaptation, because of the upfront costs, versus the benefits in terms of future (and thus discounted) benefit streams.

I7. Risks to subterranean and surface infrastructure from subsidence

The CCRA3 Technical Report reports that ground subsidence can occur due to shrinking and swelling of clay soils due to changes in soil water content. Most subsidence is as a result of shrinkage and swelling of high plasticity clays which are typically found in the south and east of England. Damage to infrastructure often occurs as a direct result of interaction with vegetation and associated water content changes. The majority of damage from subsidence occurs to residential and commercial property. However, transport infrastructure and buried infrastructure is also vulnerable to damage and disruption due to subsidence effects. Shrinkage and swelling of high plasticity earthworks can disrupt rail track alignment leading to speed restrictions and disruption to services. Road pavements can also be damaged, though this is considered a low risk due to more modern compaction methods used in the highway network. Buried electrical cables are sufficiently flexible to accommodate small movements due to shrink swell subsidence and are usually located at depths where little movement occurs. The potential for increased levels of leakages and burst frequency in water pipes due to shrink swell damage has been identified by water supply companies.

<u>Valuation</u>
As highlighted in the CCRA3 Technical Report (Chapter 4), there are some potential risks for rail (but lower risks for highway pavements) as well as potentially other surface infrastructure and some risks to buried infrastructure. However, there is little quantification of potential risks, and thus monetisation is difficult.

The analysis of residential subsidence (H5: Risks to building fabric) reports that there have been major increases in claims in hot and dry years, and it quantifies the future risk from climate change, which is significant in some regions of the UK, notably in England. If subsidence was an issue for infrastructure, then it might be expected to see similar increases in road and rail (and other infrastructure) damages, especially in the same geographical at-risk areas. However, there are also more localised subsidence issues, which could be exacerbated by climate change.

Impacts of subsidence on railways is captured in the Network Rail Schedule 8 costs (2017) which provide an indication of the type of weather event causing delays and the associated cost of compensation (2017). Costs allocated to subsidence average around £45 million over the period (2005-2016). The review has not found data for road subsidence.

The CCRA3 Technical report highlights that analysis by the British Geological Survey (2018) indicates climate change could increase risks in areas where subsidence is already a risk, and particularly in the south east. Overall, there is only limited information on the scale of risks. This makes it very difficult to even estimate the indicative order of magnitude, but it is considered most likely this is a medium ranking (£tens of millions/year).

Table 31 Valuation of I7. Risks to subterranean and surface infrastructure from subsidence.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Medium	Medium	Medium	Medium	Medium	
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

Most information is on repair costs, i.e. after subsidence has occurred (especially for residential and commercial properties). As highlighted above, there are some potential risks for rail tracks (but lower risks for highway pavements) as well as potentially some risks to buried infrastructure. There are some low-regret options, e.g. increased monitoring in higher risk areas, as well as vegetation control, but there appears to be little information on the costs and benefits for future climate risks.

I8. Risks to public water supplies from reduced water availability

The CCRA3 Technical Report (Chapter 4) draws on research commissioned for CCRA3 (HR Wallingford, 2020[ccliv]). The UK as a whole currently has a supply/demand surplus of 950 Ml/day. The research reports that without adaptation and under a central population growth scenario, a deficit across the UK of between around 1,220 and 2,900 Ml/day (2°C and 4°C range) is projected by the late century. This equates to the daily water usage of around 8.3 to 19.7 million people (based on the present day average per capita consumption of 140 l/h/d) though this deficit is concentrated in England. Although population growth is a key driver of this deficit, climate change and increasing drought resilience are key contributors. To maintain the current levels of risk management (to the worst historic drought) in the face of rising population, environmental and climate pressures by the 2050s, would require additional capacity of about 2,700-3,000 Ml/day in England (NIC, 2018[cclv]). While there is already adaptation, driven by 5-yearly Water Resource Management Plans which take an outlook of at least 25 years and already consider climate risks, there will need to be further action to manage the UK-wide supply-demand balance.

Valuation

Valuation of this risk is presented in Chapter 5 H10: Risks to water quality and household water supplies, and also overlaps with Chapter 6: B3. Risks to businesses from water scarcity.

The risk is presented in Chapter 5 to allow consideration of supply and demand issues together.

There are some additional aspects that are highlighted here. An increase in water demand, associated with a warmer climate, will have additional effects through increased energy use. The additional costs of increased electricity demand for water supply and treatment was estimated at €1.5 billion/year by 2050 and €5 billion/year by 2100 for the A1B scenario across Europe (Mima et al, 2012[cclvi]). There is therefore an additional cost to H10, associated with the increased electricity use, which could be valued using the long-run variable cost (LRVC) of electricity supply (BEIS, 2019). Note that the move to net zero would remove the externalities associated with rising electricity use, but the LRVC would still be significant.

Some European studies have also estimated high additional impacts for waste-water and sewage networks and treatment (though mostly using adaptation as a proxy for damages). Hughes et al. (2010[cclvii]) estimated adaptation costs for all water services (i.e. water resources, treatment and networks; sewage networks and treatment) at US($)110 billion (cumulative) for Western Europe, in the period 2010-50.

The valuation of water supply risk is presented – but note this needs to be considered alongside H10 and B3 to avoid double counting.

Table 32 Valuation of I8. Risks to public water supplies from reduced water availability.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK						
England	Medium	High	High	High	High	
N. Ireland	Low	Low	Low	Low	Low	
Scotland*	Low	Low	Low	Low	Low	
Wales	Low	Low	Low	Low	Low	
Confidence	Medium	Low-Medium	Low-Medium	Low-Medium	Low-Medium	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

There are estimates in the literature on the benefits of further action. In terms of the supply side there are several studies that have considered additional measures, but these focus more on drought. Water UK (2016[cclviii]) estimated that a 'twin track' approach of demand management coupled with development of new resources and potential transfers is the most suitable strategy for providing drought resilience in the future. They estimated that total costs per annum for all potential future scenarios (under the business as usual base demand management strategy) to maintain resilience at existing levels in England and Wales are between £50 million and £500 million per annum in demand management and new water resource options. If resilience to 'severe drought' is adopted, this increases to between £60 million and £600 million and for resilience to extreme drought, between £80 million and £800 million per annum. The National Infrastructure Commission (2018[cclix]) estimated that in England alone the total costs between 2020 and 2050 of implementing emergency measures to provide household water supply during a 0.5% drought, weighted by the occurrence probability, range between £13 and £16 billion. The total costs over the same period of implementing emergency measures against a 0.2% drought range between £21 billion and £27 billion (costs on a present value basis (2018 prices) weighted by the occurrence probability). Atkins (2018[cclx]) used cost benefit analysis to build marginal abatement cost curves of emergency measures, i.e. when drought severity is beyond the capacity planned for through long-term water resources planning. This included examples for the Thames Basin. The results indicate that many emergency measures would be challenging to implement, provide uncertain yields and incur significant costs (Atkins, 2018).

There is also a suite of demand side measures that can be introduced by homes, many of which are no-regret and low-regret. Water UK (2016) assessed a twin track approach of demand management coupled with appropriate development of new resources and potential transfers as being the most suitable strategy for providing drought resilience in the future. They estimated that total costs per annum for all potential future scenarios (under the business and usual base demand management strategy) to maintain resilience at existing levels in England and Wales are between £50 million and £500 million per annum in demand management and new water resource options. If resilience to 'severe drought' is adopted, this increases to between £60 million and £600 million and for resilience to extreme drought, between £80 million and £800 million per annum. There are several studies that have looked at demand side measures for households that identify a large number of low- and no-regret options. The study by ARUP (2008[cclxi]) looked at a range of water saving measures, and estimated costs and pay-back times. A similar study was commissioned by the CCC (Davis Langdon, 2011[cclxii]) looking at cost-effectiveness of alternative household options, and this was updated by Wood Plc (2019[cclxiii]), updating a previous cost-curve study. These studies identify estimated measures with benefit to cost ratios above 1 for different house types, comparing new-built vs discretionary retrofit. The study provides unit-cost estimates for different measures, and calculated cost-curves to show their relative cost-efficiency. When considering wider benefits from a societal perspective (including avoided GHG emissions), additional no-regret measures are identified. Generally, end-of life upgrades and measures installed in new builds were more cost-effective compared to retrofits. These studies highlight the high economic benefits of further action.

Research by Artesia (2019) for Water UK assessed the savings, costs and benefits of 18 water demand reduction interventions. It was estimated that with concerted effort by government departments, regulators and water companies, £64 benefit for every £1 spent could be achieved. The report found that the best strategy to maximise demand reductions involved mandatory water labelling and increased smart metering (above that in current water company plans). It was estimated that a 2,300 Ml/d reduction in demand beyond current ambitions could be achieved through these measures.

I9. Risks to energy generation from reduced water availability

The CCRA3 chapter sets out that the electricity supply industry is important for surface and groundwater abstractions in England. Around 60% (by capacity) of all thermal power plants in the UK are cooled with sea and tidal water, including all nuclear generation, with the remainder relying on freshwater for cooling. Current risks to thermal plants arise from potential restrictions to either abstracting or discharging water into freshwater systems due to periods of low rainfall and/or in combination with elevated temperatures. While this has been an issue in Europe, significant interruptions to inland thermoelectric generation have not been reported to date in the UK. For future risks, there are potentially areas of the UK where existing inland thermal plant source water could be vulnerable to low flows and drought. However, the Technical Report (Chapter 4) highlights the Net Zero commitment could see a significant turn over in current thermal plants and thus reduce the potential risk of the current plants on the system. Therefore, it is potentially more important for climate risk to consider new power plants – but also other investments (e.g. hydrogen economy or carbon capture) associated with Net Zero that have water demand.

Valuation

To date, there have not been major incidences where hot summers have led to problems with cooling water in the UK. However, this has been an issue in Europe, notably with the effect of the 2003 hot summer in France. A number of studies have looked at the impacts of climate change on power plant cooling water for thermal power plants (nuclear and fossil). The ToPDAd study (Perrels et al., 2015[cclxiv]) assessed the possible future impacts of climate change for nuclear power in France, using economic modelling, and estimated losses could vary between tens and several hundred billions of euros per decade by 2100 (for current infrastructure), though found adaptation strategies can reduce the losses significantly.

Tobin et al. (2018[cclxv]) looked at the potential impacts on thermal power generation for different warming scenarios (1.5, 2, 3°C) and for different regional climate models, based on analysis of changing streamflow and water temperature (for river sited plants). This found quite large negative effects for all countries in Europe, including the UK, due to a combination of higher water temperatures and reduced summer river flows, reducing the usable capacity of thermoelectric power plants using river water for cooling. The magnitude of the decreases was estimated at ~ 5% for 1.5°C, 10% for 2°C and ∼15% for 3°C for most countries. Note that in the UK, all nuclear plants use sea water for cooling, so this risk would only apply to thermal river cooled plants.

However, these assume a static electricity generation mix. In practice, the UK generation mix is changing very rapidly, and the proportion of conventional river-cooled thermal fossil plants will likely be very much lower by 2030 and zero by 2050. It is highlighted that the Government has committed to phase out coal fired generation by 2025, and for offshore wind to produce 30% of electricity in 2030, and the CCC net zero analysis suggested (CCC, 2019[cclxvi]) that low-carbon power could reach 75-85% of overall generation by 2030.

The key issue with this risk is therefore on what replaces the current electricity supply mix, i.e. the risk is determined by the nature of the future energy mix towards Net Zero. The CCC report (2019) highlights the continued role of renewables, but also the need for gas and/or biomass coupled with carbon capture and storage, as well as an increase in the use of hydrogen. These all require water, and as highlighted in the Technical report, there is thus the potential for the UK energy systems' vulnerability to reduced water availability to increase or decrease. This is linked to the previous risk (I8) on water availability and the supply-demand balance. While the risk is considered low currently, the future risk depends on the future energy mix, and thus is unknown.

Table 33 Valuation of I9. Risks to energy generation from reduced water availability.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	Unknown	Unknown	Unknown	Unknown	
Confidence	High	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

The costs of further monitoring, and some strategic analysis to look at water related risks (water demand and flooding) for Net Zero generation, are low-regret options and would have clear benefits through the information provided.

For existing thermal plants, there are low regret adaptation options centred on monitoring of risk levels, including early warning and subsequent emergency management during extremes. In other European countries, where these risks have already materialised, adaptation options have focused on demand management and there is some analysis (Perrels et al., 2015) of the economic benefits of demand management options (for industry) and the potential use of smart grids to help manage non-essential energy use during these events; these might provide options should risks increase in the UK. There are also studies that look at the economic benefits of alternative cooling systems (Després and Adamovic, 2020[cclxvii]), which find high benefits, but these tend to be focused on nuclear with river water abstraction (which is not relevant in the UK) or thermal plant (which are being phased out under Net Zero), however these technologies are suitable for biomass and CCS sites.

For the new mix of energy generation for Net Zero, and especially for biofuel, biomass, CCS and hydrogen, the most obvious no regret option is for further analysis of the possible risks with respect to water demand of new generation plant, the number required, and the linkages with Risk I8 on water supply. These factors could lead to important adaptation options around siting and technology options, and at the very least, the cost implications for any water use under a changing climate.

I10. Risks to energy from high and low temperatures, high winds, lightning

The CCRA3 Technical Report (Chapter 4) considers a number of possible risks to energy from different hazards. It identifies a range of potential impacts from high temperatures, which can reduce the amount of electricity generation from thermal generators and the efficiency of photovoltaic cells.

High temperatures can: reduce the amount of power which can be transmitted and distributed; cause line sag; affect the running of gas compressor stations and solar heat; and increase the potential risk of faults on the electricity network. It reports that studies on the impacts of lower temperatures on the energy sector are generally related to the coincident effects of snow, sleet and ice, which are associated with line faults. It identifies the risk of high winds on power lines, and more generally changes in the wind regime to wind power (noting also that high wind speeds can reduce output from wind farms if speeds are above their safety cut-offs). The major impacts of lightning for energy infrastructure are physical damage, fire, power surge, and shock wave (i.e. strong pressure wave). The CCRA3 report also highlights that future risks related to the energy sector are also influenced by the future profile of energy demand and supply, and the net zero target.

Valuation

Climate change – and changes in temperature and wind regimes - will have effects on energy supply, notably on hydroelectric generation (covered in a previous risk), wind, solar and biomass, but also on thermal power (nuclear and fossil) plants via thermal efficiency (use of water is covered in a previous risk). Note that impacts relating to demand are covered in Chapter 5 (heating and cooling demand). There are two main risks that have high potential impacts, in economic terms. The first is from the influence of climate change on wind. These impacts require consideration of changes in the wind regime overall, and not just high winds. The second main risk is the potential effect on thermal generation efficiency.

Wind storms and lightning

There are existing impacts from wind storms affecting electricity generation – but especially transmission. These can lead to outages, and impacts on welfare through electricity not delivered, which is typically valued using the Value of Lost Load (VoLL).

Watkiss et al. (2006[cclxviii]) looked at the costs of previous storms, e.g. the storms of October 2002, which caused widespread damage to the electricity network and resulted in the loss of electricity supply to 2 million customers. The analysis looked at the costs of this event using the energy not delivered using the Value of Lost Load (VoLL)[8]. The cost was estimated at approximately £30 million, which adjusted for current prices would be closer to £40 million. However, the frequency of such an event is quite low, and an annualised value was closer to £3 million. The analysis also estimated that such events might increase with climate change. While noting the high uncertainty, it indicated the annualised value might increase by 60% by the late century. The UKCP18 projections of changes in windstorms highlight the high uncertainty, although analysis by ABI / Air Worldwide and Met Office (2017[cclxix]) projected increases in major storms for both the 1.0% exceedance probability (100-year) loss, and the 0.5% exceedance probability (200-year) loss.

Karagiannis et al. (2019[cclxx]) looked at the vulnerability of critical energy infrastructure to storms, with emphasis placed on the power grid. Their approach combines a future projection of the recurrence interval of selected storm scenarios and the assessment of the estimated economic losses incurred by critical infrastructure (repair costs) and those resulting from the disruption of daily economic activity due to the outage caused by the storm. They derived the projected peak wind speed of the 10-, 50- and 100-year storm scenarios for five time periods, i.e. from 1981 to 2010, from 2011 to 2040, from 2021 to 2050, from 2031 to 2060, and from 2041 to 2070 together with a RCP8.5 scenario. The authors found that for each recurrence interval, the cost to repair the damage to overhead lines and the economic losses from the interruption of the daily economic activity each amounted to about half of the total losses. The total expected losses were found to be just above €40 million for the 10-year storm scenario and increase by approximately 10% to ~€45 million of the total for the 50-year and the 100-year storms (there is no statistically significant increase of the economic impact from the 50-year to the 100-year storm). This change seems to be driven by the repair cost increase. Nevertheless, they found no statistically significant increase of the economic impact from the 50-year to the 100-year storm, and highlighted the caveat of assuming constant power outage duration across all

[8] The study used a value of VOLL from the electricity pool in England and Wales. It ranged between €3.8/kWh for a one-hour outage to €1.8/kWh for an outage of longer than 24 hours. Other studies, however, do find higher values.

scenarios. The duration of the power outage is indeed an uncertain determinant of the expected losses resulting from the disruption of the daily economic activity. The study found that the 10-year scenario comes with the highest level of risk, more than three times that of the 50- year scenario, and the 100-year scenario is associated with the lowest level of risk.

There is also a potential compounding effect from increased vegetation growth, and the risks of wind damage, as wind-blown vegetation is a major source of damage to power lines. There has been some analysis of this, and the potential increase in vegetation management costs, which can be considered as an impact or an adaptation (Metroeconomica, 2004[cclxxi]).

There are occasional impacts from lightning, although energy infrastructure is normally resilient to this risk. The CCRA3 Technical Report (Chapter 4) highlights the power outages in England and Wales in August 2019, which were triggered by a lightning strike on the Eaton Socon-Wymondley circuit between Cambridgeshire and Hertfordshire, albeit combined with other factors, and led to interruption of the electricity supply of over 1 million consumers. However, it is not clear how climate change will affect the incidence of lightning strikes and thus this future risk.

It is also highlighted that projected decreases in frost days and icing days could reduce the risk to the electricity networks from faults related to frost and ice.

Wind generation

There is clearly a potentially large effect from wind regimes on wind power. These could include positive or negative effects in terms of wind generation, but also potentially negative changes in extremes (low wind or high winds) that might affect generation. This is discussed in the next risk (I11. Risks to offshore infrastructure from storms and high waves). This risk is potentially important, because of the shift to offshore wind in the UK. In 2019, onshore and offshore wind generated similar amounts of electricity (32 TWh) (DUKES, 2020), although there is higher installed capacity of onshore wind (14 GW versus 10 GW). However, going forward the main expansion will be in offshore wind in line with new government targets.

Thermal plants and efficiency

In Europe, a number of studies have looked at the impacts of climate change on thermal efficiency for thermal power plants (nuclear and fossil). Mima and Criqui (2015[cclxxii]) estimated that thermal and nuclear power generation could be reduced by up to 2-3% (thermal) and 4-5% per year (nuclear) for current plants (A1B) and estimated the potential costs of these changes using the POLES energy model.

Tobin et al. (2018[cclxxiii]) looked at European power generation under 1.5, 2 and 3°C of warming. Estimates were calculated over three periods which represent the earliest 30-year periods with time-averaged global mean temperature increase compared to the ‘pre-industrial period’ 1881‑1910, i.e. 2004-2043 for the 1.5°C scenario, 2016-2059 for the 2°C and 2037-2084 for 3°C. The authors project quite large reductions in thermoelectric generation with 5-10-14% reductions (for the 3 scenarios), including for the UK, although this includes a combination of different risks (including cooling water, see previous risk). A reduction of this size would be very significant for the current UK energy mix, but the magnitude in the future depends on how the energy mix changes towards net zero. For example, while conventional gas fired plants will no longer be in operation in 2050, there could still be gas with carbon capture (and biomass with carbon capture). The study also found a very small effect on PV output, finding a small reduction of between 1 and 3%.

Després et al. (2020[cclxxiv]) also used the POLES model and looked at electricity supply in Europe. The changes in power generated for the UK (and Ireland) are shown below. The scenarios represented are based on 11 climate models, with RCP 4.5 and RCP 8.5, to estimate changes for global warming levels of 1.5, 2 and 3°C warming. This was undertaken for a static and a dynamic scenario. The former looks at the effects of climate change only. The static analysis indicates little impact on nuclear and thermal generation. For wind it indicates very modest rising wind generation for 1.5°C and 2°C scenarios, but a fall for 3°C, although even the latter is only approximately 2%. It is highlighted that the impacts on thermal plants for the UK are projected to be much lower than for other studies.

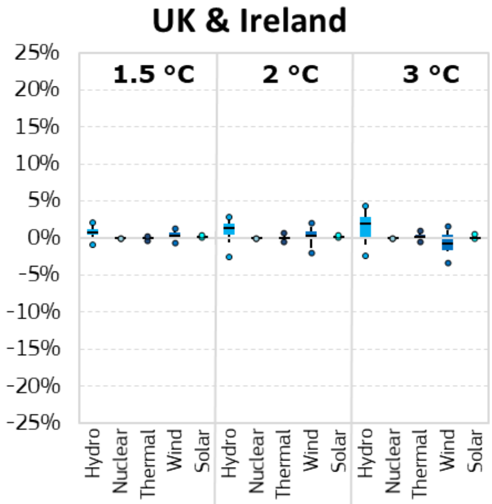


Figure 14 Climate change impacts by energy source in Europe for current supply mix and generation. Source: Després et al (2020).

Dots indicate the extreme scenarios; vertical lines indicate the spread, coloured areas indicate the two middle quartiles separated by the median line. All effects other than climate impact on electricity supply are neutralized; only the relative differences of production of each electricity source are shown.

The dynamic analysis takes account of changes heating and cooling demand, as well as changing energy prices in response to climate effects on supply. It also includes socio-economic change (and thus changing demand) as well as policy changes, and thus new generation technologies (e.g. carbon capture and sequestration). The effects are larger in this case, though still modest.

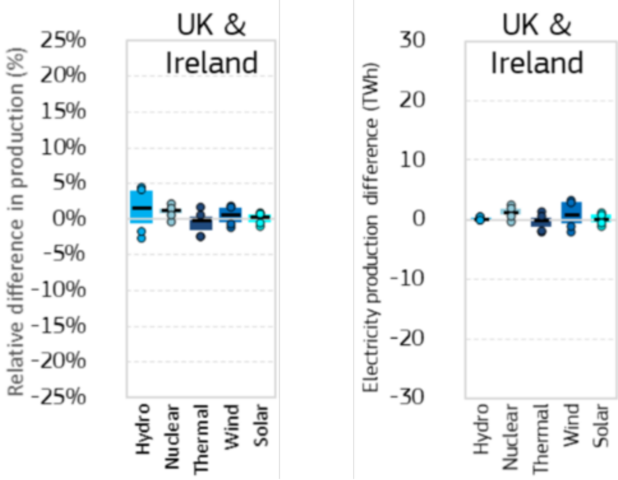
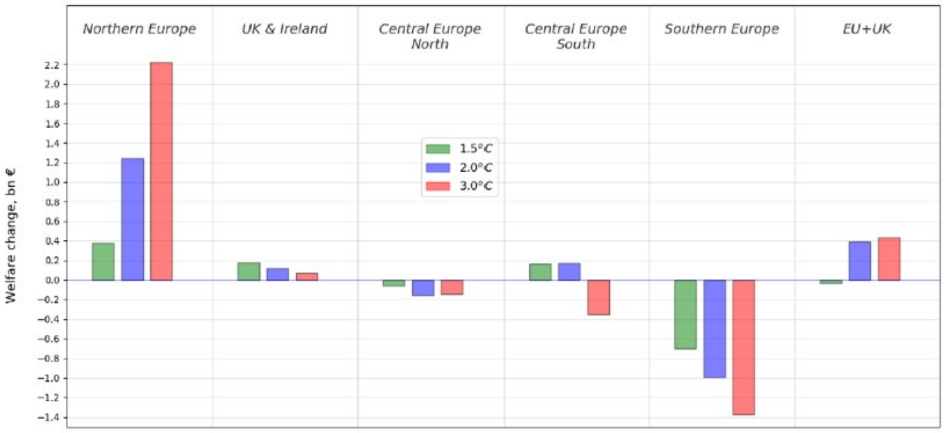


Figure 15 Climate change impacts in 2050 production by energy source in a dynamic scenario, in Europe, by region, in relative (%) and absolute (TWh) terms. Source: Després et al (2020).

These estimates were also fed into a CGE model (Szewczyk et al. 2020[cclxxv]), to look at the changes in production costs, and subsequently, changes in welfare, for varying global warming levels. The estimates for the UK indicated a very small decrease in production costs (though less than 0.5%). This in turn led to welfare gains. For the UK and Ireland, the change is positive but small, in the range of 0.07 bn € to 0.18 bn €.



Region	Welfare (bn €)			Welfare (% of GDP)		
	1.5°C	2°C	3°C	1.5°C	2°C	3°C
Northern Europe	0.38	1.24	2.22	0.044	0.143	0.256
UK & Ireland	0.18	0.12	0.07	0.009	0.006	0.004
Central Europe North	-0.05	-0.16	-0.14	-0.001	-0.004	-0.004
Central Europe South	0.16	0.17	-0.35	0.006	0.006	-0.013
Southern Europe	-0.70	-0.99	-1.37	-0.022	-0.032	-0.044
EU + UK	-0.04	0.39	0.43	0.000	0.003	0.003

Source: PESETA IV, 2020.

Figure 16 Change in welfare (bn €) for the three climate scenarios. The losses reflect the change in production cost of electricity with respect to current. Source: Szewczyk et al. (2020).

Valuation summary

The estimates of monetary values for this risk are complicated by the wide range of risks, but also the uncertainty. Indeed, it is possible that there could be net benefits, from positive changes in supply for some technologies.

Table 34 Valuation of I10. Risks to energy from high and low temperatures, high winds, lightning.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Medium	High to very high (but potentially positive or negative)	High to very high (but potentially positive or negative)	High to very high (but potentially positive or negative)	High to very high (but potentially positive or negative)	
Confidence	Medium	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

There is emerging information on the costs and benefits of climate smart design of energy generation including renewables. There is less evidence on the risk levels and potential costs and benefits of climate smart design for the new generation of technologies that will be developed to meet Net Zero, though there are obvious early low regret actions to further investigate these.

There are several hazards and a number of different energy generation technologies within this risk, each of which has particular adaptation responses.

The risk of wind damage to energy supply and transmission infrastructure is one area, and there may be compounding effects from increased vegetation growth. There has been some analysis of these aspects, and the potential increase in vegetation management costs, which can be considered as an impact or an adaptation) (Metroeconomica, 2004[cclxxvi]), though there are additional options, e.g. wind fences/breaks, circuit breakers, etc. The potential changes in wind regimes and wind power generation are highlighted as a watching brief above: there are technical design as well as operational management options to address potential changes should these emerge.

There is a more general approach for adaptation, with the inclusion of climate risk assessment as part of project design and financial and economic appraisal (see also the Green Book Supplementary Guidance on Accounting for Climate Change, Defra, 2020[cclxxvii]). However, there is less evidence on the risk levels and potential costs and benefits of climate smart design for the new generation of technologies that will be developed to meet net zero: an obvious early low regret action is to further investigate these.

I11. Risks to offshore infrastructure from storms and high waves

The CCRA3 Technical Report (Chapter 4) considers the risks to offshore infrastructure, associated with the oil and gas industry, wind, tidal stream and wave energy as well as communications, gas pipelines and power cables on or under the sea bed. The main vulnerabilities are identified as storms and high waves, affecting structures, operation and revenues (as well as maintenance access). It considers the current risks to offshore infrastructure are low, based on good evidence, but with an increasing risk over time, notably around offshore renewable energy infrastructure, with less confidence in the evidence. The main issues are identified with increasing offshore renewable energy infrastructure, although these have relatively short lifetimes, and the large fleet of oil and gas platforms, which may be repurposed for carbon sequestration storage and thus remain operational beyond their initially-intended lifespan.

<u>Valuation</u>
The analysis has considered impacts on oil and gas and offshore wind.

<u>Oil and gas</u>
There is a large stock of oil and gas infrastructure around the UK, and these can be impacted by extreme events. In other regions, notably the US Gulf Coast (Cruz and Krausmann, 2008[cclxxviii]) wind storms have led to major damage and lost production (totalling $billions) and have also impacted via oil spills. However, these areas face much higher windspeeds than the UK in the form of hurricanes. In general, climate change is projected to increase both the severity and the frequency of weather events that could impact on the whole value chain of oil and gas, from production to transport and distribution (Cruz and Krausmann, 2013). There is generally perceived to be a low risk to offshore oil and gas infrastructure in the UK, though there is little quantified projected analysis to back this up.

<u>Offshore Wind turbines</u>
Climate change may affect the frequency and intensity of storms, storm tracks, wind velocity, and wave heights. Changes in wind regimes as a consequence of climate change can affect wind power generation through increased variability in generation, damages to wind turbines due to extreme weather events (or shut-down when high wind speeds are reached) and intermittency in generation leading to increased firm backup capacity (Chandramowli and Felder, 2014[cclxxix]). However, the projections of changes in wind strength, wind regimes, storm strength and storm tracts from climate change are highly uncertain.

There are a series of studies that look at wind-power (onshore and offshore). Tobin et al. (2014[cclxxx]) assessed the potential impacts of climate change on wind generation for a 2°C scenario for Europe and estimated a potential reduction in power generated by wind of 0 to 2% for the UK. Tobin et al. (2018[cclxxxi]) produce updated estimates, for 1.5, 2 and 3°C scenarios, and find for the latter (3°C) wind power production could reduce by as much as 5% in the UK. Carvalho et al. (2017[cclxxxii]) reported a general decrease of future wind energy density over much (but not all of) Europe, and with seasonal differences. By the end of the current century differences in terms of wind energy density can reach up to +30% in the Baltic regions and -30% in Eastern Europe; and in winter, increased density is projects in northern-central Europe and a decrease in the southernmost European area (Carvalho et al., 2017).

Després et al. (2020[cclxxxiii]) in the PESETA IV study looked at energy supply in Europe. They identify modest levels of impacts, similar to other studies above, including the potential for a change in wind generation (TWh) in the UK, i.e. with potentially positive or negative effects of a few %. The COACCH project (Schleypen et al., 2020[cclxxxiv]) carried out an econometric analysis of historic wind regimes and then looked at future potential effects in Europe under Representative Concentration Pathway (RCP4.5 and RCP8.5) in two time periods (2030-2050, and 2050-2070) compared to the reference period (1986-2005). The analysis estimated that across Europe, under RCP4.5, load factor capacity from wind power will decline by 5.6% by 2050 compared to the reference period of 1986-2005, while by 2070 the reduction will be 7.3%. Under an unmitigated climate change scenario of RCP8.5, load factor capacity is projected to decline by 6.9% by 2050 while by 2070, the declines are projected to be 9.7%. However, for the UK, under a RCP4.5 scenario the study estimates a slight increase in wind load factor capacity by 2050, except for Scotland (-5%), with more marked increases (up to +20%) in the south east and Northern Ireland. However, it also estimated a general decrease (-10%) across the UK by 2050 and 2070 under a RCP8.5 scenario.

There are some studies specifically for offshore wind. Hdidouan and Staffel (2017[cclxxxv]) examined the change in capacity factor for offshore wind around the UK, to 2050 and 2080. They found a small (<1%) change for farms east of England in the North Sea, with small increases in capacity factor moving further north, reaching 5% to the north and west of Scotland. This indicates changes that are generally small, i.e. within the year to year variability, although other studies indicate possibly larger effects due to North Atlantic Oscillation (Brayshaw et al. 2011[cclxxxvi]). In a case study, Hdidouan and Staffel (2017) project that there would be a 0.9% increase in average annual capacity factor for the 3.6GW Dogger Bank wind farm in the North Sea in the near-term (RCP 6.0, 2011–2030), but no increases in capacity factor by 2060 and 2090.

More frequent high wind speeds will lead to greater loss of wind power due to the way the wind turbines operate. Storm control systems stop wind turbines when the wind speed exceeds a certain value. Internationally there are examples where very large tropical windstorms damaged turbines with high costs[cclxxxvii]. However, windspeeds are lower in the UK, and further, there is very high uncertainty on storm projections which make it difficult to accurately project the potential impacts.

ABI / Air Worldwide and Met Office (2017[cclxxxviii]) estimate the impact of three global temperature scenarios on the frequency and intensity of UK windstorms and estimate that that under the RCP4.5 and RCP8.5 scenarios, the frequency of storms will increase over the majority of the UK, apart from over southern UK where the number of storms will decrease. Of more importance, the study estimates possible increases of up to 40% in the 200-year return period loss, and approximately up to a 30% increase in the 100-year return level loss. These would imply potential increases in higher speed storms, and the potential for associated wind turbines damages.

Most literature indicates the potential changes in (average) wind load capacity are likely to be modest and they are also uncertain (and vary across regions). Nonetheless, even small changes (incl. in the number of windstorms) might have large economic consequences. Recent announcements (2020[cclxxxix]) have set a Government target for offshore wind to meet one third of UK electricity demand by 2030, reported as 30GW being built by 2030 (with the total offshore wind industry reaching 40GW by 2030, as 10 GW is already installed). This will involve an estimated £50bn in capital investment[ccxc]. This can be translated into electricity produced (GWh) using load factors. Offshore wind currently has a load factor of 40%[9] (DUKES, 2020) and generates 32 TWh. Applying

9 The load factor is the ratio of the amount of electricity actually produced by a turbine or wind farm over a period of a year divided by the amount of output that would have been produced had it operated at full capacity .

the same load factor to 40GW would mean generation of approximately 140 TWh, and applying the long-run variable costs of energy supply (LRVCs), even a 1% (+ or -1.4TWh) change would have a value of £150 million/year. By 2050, the CCC Net Zero projection involves 75 GW of offshore wind capacity, which would require ~7,500 offshore wind turbines to be operating in UK waters (CCC, 2019) and thus further increase the magnitude of any potential effects.

In practice the combination of changes in climate variability and wind speeds (including high speeds or storm tracts) could be quite important. The CCRA3 Technical Report highlights that should high winds increase, or variability increase, this could affect the resilience of the energy system given the large projected switch to wind.

There are potential risks to physical structures, although these have not been quantified. Wilkie and Galasso (2020[ccxci]) evaluate the potential impact of climate-change scenarios on various offshore wind turbine performance metrics, including fatigue damage and financial losses (cost of direct damage). They report that the costs of replacing non-structural components range from €13,000 to €230,000/component, and that the peak in fatigue damage occurs around the rated mean wind speed of 11.4 m/s, and that fatigue damage increases at a faster rate than the average power generation. Both fatigue damage and structural safety are found to be sensitive to changes in the environmental conditions of the site.

Subsea cables are notably exposed to changes in the offshore environment such as scour and sediment transport due to climate change, and damage to cables is a major cause of supply disruption for offshore wind farms (Dinmohammadi, 2019[ccxcii]), although future risks have not been quantified. Finally changes in the offshore conditions (Dinwoodie et al. 2018[ccxciii]) may also affect the accessibility of structures for maintenance, inspection and crew transfer.

The results are presented below, based on the analysis of offshore wind, and that even a very modest change would have large economic consequences (noting that these could be positive or negative) because of the very large expansion of offshore wind in the UK.

Table 35 Valuation of I11. Risks to offshore infrastructure from storms and high waves.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	High (but could be positive or negative	High (but could be positive or negative	High (but could be positive or negative	High (but could be positive or negative	
Confidence	High	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

<u>Adaptation</u>

As with the previous risks, the potential changes in the offshore wind regime and implications for offshore energy infrastructure (notably offshore wind), as well as other offshore risks (e.g. wave regimes), requires periodic review, but there are technical designs for turbines as well as operational management options to address potential changes should these emerge, and a general recommendation on the use of climate risk assessment in new project design and appraisal. Offshore, subsea cable failures are currently the most important failure risk; these can occur from changes in tidal flows (Dinmohammadi et al., 2019) and might warrant further consideration of risks.

I12. Risks to transport from high and low temperatures, high winds, lightning

The CCRA3 Technical Report (Chapter 4) considers the risks from temperature, winds and lightning for different transport modes and concludes the magnitude of these risks is medium. It also highlights a new issue for the transport sector, relative to CCRA2, because of the changes needed to meet the UK's Net Zero commitments. This will lead to new interdependencies with electricity generation, transmission and distribution networks, as well as the digital/ICT sector.

Valuation

The risks of climate change for the transport sector primarily arise from extreme events, such as flooding, heat waves, and storms. As well as direct damage costs to infrastructure, these extremes have economic costs from passenger and freight transport disruption (affecting travel time) and can also affect the likelihood and severity of accidents. There are also wider indirect effects from transport disruption, affecting the supply of goods and services, which can be significant for major events.

The potential impact of flooding on transport was included in I2. (river, surface and groundwater) and I3 (coastal flooding). Risks to bridges were included in I4 and slope and embankment failure in I5. This risk therefore covers additional risks from extreme heat and high winds.

Rail

The potential risks of high temperatures on the rail networks, and the potential economic costs of rail buckling risks under climate change have been previously estimated in the UK (Watkiss et al, 2006[ccxciv]; Dobney et al., 2010[ccxcv]; CCRA1 – Thornes et al., 2011[ccxcvi]; Alvater et al. 2012[ccxcvii]). At extreme high temperatures the railway network is prone to damaging and expensive rail buckles. In order to reduce the risk of a rail buckle, emergency speed restrictions are introduced which can be costly. Valuation includes the increased maintenance costs (or repair costs) and the travel time delays from speed restrictions. Travel time is routinely included in transport appraisal (DfT, 2019[ccxcviii]), including work and non-work time, and government values are available for use by mode. These should also take into account the increase in the value of travel time in future years, and guidance recommends that both the work and non-work values of time are assumed to increase with income over time (real GDP growth per head) in a linear way. Previous hot years have led to economic costs, with most recently, Ferranti et al. (2018[ccxcix]) estimating additional costs during 2015 of £16 million. Looking to future climate change, Thornes et al. (2011) estimated modest costs of a few million/year by the 2050s. Higher estimates were projected by Dobney et al. (2009) with the total annual costs of rail related heat-related delays estimated to double to £23 million during extreme summers without changes in maintenance regimes. There are also some risks of overheating of equipment both on rail infrastructure (e.g. signals) and trains, which could involve both further repair and travel delay costs.

However, an important issue will be the need for the switch to net zero for the rail sector, which means either full electrification or some form of zero carbon locomotives (hydrogen). The CCRA3 Technical report also highlights that modern signalling is more susceptible to heat due to its dependence on electric and electronic components. The 2019 heatwave did lead to some impacts on electric trains, because electric wires sagged in the heat (NIC, 2020[ccc]).

Additional line-side fires along railways have been reported as a significant issue in earlier hot years, with previous estimated costs of £1 million over the 1995 summer (Thornes, 1997[ccci]). There are no projections of costs for the future, but the risks of these fire related events are generally projected to increase.

There is also an issue of over-heating and/or the increased demand for cooling (from air conditioning) of rail vehicles – noting that there will either be increased passenger discomfort or increased cooling in summer, which will have economic costs because of increased energy demand. This review has not found estimates of the additional cooling costs, but presumably there is information from continental railways. For example, there is some information that suggest auxiliary energy use for trains (presumably mostly for cooling) is 11% of total consumption of modern trains in Spain[cccii]. While cooling is a low proportion of railway energy demand, given the size of the network, even a modest increase would have a significant economic cost, especially for the South East. Data on energy consumption for the railways in GB (ORR, 2019[ccciii]) indicate energy use in passenger trains was 3,976 million kWh of electricity and 469 million litres of diesel. A modest increase in this (e.g. a few %) can be valued using the long-run variable cost (LRVC) of energy use. This indicates potential additional costs of £tens of millions/year.

There is also a particular issue of over-heating on the London underground. There are some reported statistics on the incidence of health effects on London Underground and more broadly on passenger discomfort, but no estimates of the economic costs.

The CCRA3 Technical Report highlights that damage caused by wind is currently a large cost to the rail system, with approximately £145 million in compensation payments (schedule 8 costs) between Network Rail and train operating companies over the 2006 – 2016 period (Network Rail, 2017[ccciv]). Wind impacts have the highest weather-related cost implications for the railways, in addition to safety concerns from fallen trees (Network Rail, 2017). Much of this damage arises from wind-blown vegetation (such as trees). Climate change may influence these costs in two key ways. First, there are the projected changes in windstorms. The projections of changes in windstorms are uncertain, including the change in frequency and intensity, but also whether storm tracks could shift in the future, resulting in fewer mid-latitude storms. Some studies have indicated a small increase in the number of windstorms affecting the UK with the frequency and intensity of the most extreme windstorms increasing during the winter months - see ABI / Air Worldwide and Met Office (2017[cccv]) referred to earlier. Such increases would imply potentially important increases in the economic costs of wind on the rail network, and these may increase should rail electrification increase (i.e. a switch from diesel to electric trains, and thus more electricity transmission infrastructure at risk). Second, warming temperatures are projected to increase vegetation growth and lead to increased cost of vegetation control (maintenance costs).

However, there is likely to be a reduction in some types of cold-related delays and winter maintenance costs, which will lead to benefits (opportunities).

Overall, there are potentially important economic costs to the rail sector. There are not robust estimates, but the likely additional impacts for the 2050s seem to be of the order of £tens of millions/year, with a possible upper estimate that might just exceed £100 million/year. Impacts would be greater in the 2080s.

<u>Road</u>

There has been analysis of the potential economic costs of heat on highways (including rutting and user delay costs, as well as additional capital maintenance costs). There is evidence from the 2003 summer (Watkiss et al, 2006[cccvi]) which had reported costs of repair of approximately £40 million (for a small number of regions only). Atkins (2013)[cccvii]focused on roads in England, and estimated the reduction in service life, leading to additional maintenance work and subsequent user delays, from heat from climate change. It found modest impacts. This estimated the total discounted additional maintenance costs at a present value of approximately £9 million (central scenario) rising to a present value of approximately £76 million (worst case scenario) over a 60-year period [note these are present values not annual values][10]. The associated user delay costs were estimated at present values of approximately £4.3 million (central) and £33.3 million (worst case). These imply quite modest future annual values for the central scenario, but higher levels for the worst-case.

Further issues related to higher temperatures are increased air conditioning use in vehicles and higher fuel (energy) costs. Indicative work on this in CCRA1 (Thornes et al., 2011) indicated this could be quite significant, just because even a small increase is important in aggregate, given the number of road vehicles in the UK, with potentially medium costs (£10 – 100 million/year) by the 2050s and 2080s.

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[10] The study estimated a Central scenario: Medium emissions and 50th percentile and Worst-case scenario: High emissions and 90th percentile. Climate impacts were considered for a 60 year period: from 2013 to 2072.

There are some European estimates of climate change impacts on road transport, which include positive as well as negative effects. Nokkala et al., 2012[cccviii] presents an overview of road accident costs in 2010 and in 2040 and 2070. Numbers are projected to reduce across the EU, very significantly (from € >10 billion/ annum in 2010 to €4.5-6.6 billion/annum in the 2040-2070 period). This is the result of the positive effects from the expected developments in vehicle technology and emergency systems being greater than the negative effects of changing temperatures and frequency of extreme weather phenomena. The WEATHER project (2011) estimates that in Europe by 2050 there could be a modest increase in road transport average damage costs of 5%, although this will be the result of an increase in infrastructure damage (+11%), and a decrease in service (-3%) and users costs (-7%). For the UK and Ireland road sector, the project estimated a small increase in damage costs by 2050 (+3%) compared to current levels (2010). However, a break-down of costs indicate winners (users, -13% of costs in terms of injuries, fatalities, and travel delays), and losers (+30% increase in costs for service operators; and +9% for infrastructure owners).

Cold weather is a major source of maintenance cost and travel time delays at present. It is also a major source of accidents, i.e. from ice and snow. There are likely to be potentially large benefits (opportunities) related to changes in winter maintenance regimes (e.g. gritting), reductions in winter-related accidents, and reductions in cold related transport delays. These benefits are likely to be at least as large, and potentially larger, than the additional costs of heat above. The changes to road maintenance more generally are likely to be affected by changes in the freeze-thaw regime, and these are more difficult to project and will vary across the country.

The road transport sector will also need to switch to zero carbon, which will lead to inter-dependent risks with the electricity sector.

<u>Other modes</u>
There are potential risks to inland waterways, from the combination of higher temperatures and changes in rainfall. The risks and economic costs of climate change on some waterways have been assessed in Europe, where lower flows in the Rhine and Danube might lead to a shift to smaller vessels and a minor shift in modal split, with an increased price for transportation (Bruinsma et al., 2012[cccix]) but these issues are considered minor for the UK, as there is not extensively use of inland waterways for freight.

There is less information on air transport. Airports are potentially at risk from extreme events, and the flooding of substations at Gatwick in December 2013 (see I1) demonstrates these can led to high economic costs. Higher temperatures reduce the density of the air, thus increasing the fuel needed for airplanes. However, there is no quantified projections on what this could mean in terms of potential future costs. The other influences on air transport are uncertain, because most potential costs are from extreme wind and fog, and there is less agreement on these in the climate model projections.

Nokkala et al. (2012) estimated impacts (€) on aviation in terms of airline operation costs cancellations and delays in 2040 and 2070 due to fog, wind and cold. They estimated that while there might be an increase in the mid-term, there could be reductions by 2070, although the reasons for this result are not given in the report. The authors estimated the average social cost of aviation disruption as the loss of productivity resulting from the time spent waiting. For Heathrow alone, the estimated costs are significant. However, no changes in traffic volume are taken into account. In case of expanding capacities at airports resulting in higher total movements per time period, even higher values could be expected (Nokkala et al. 2012).

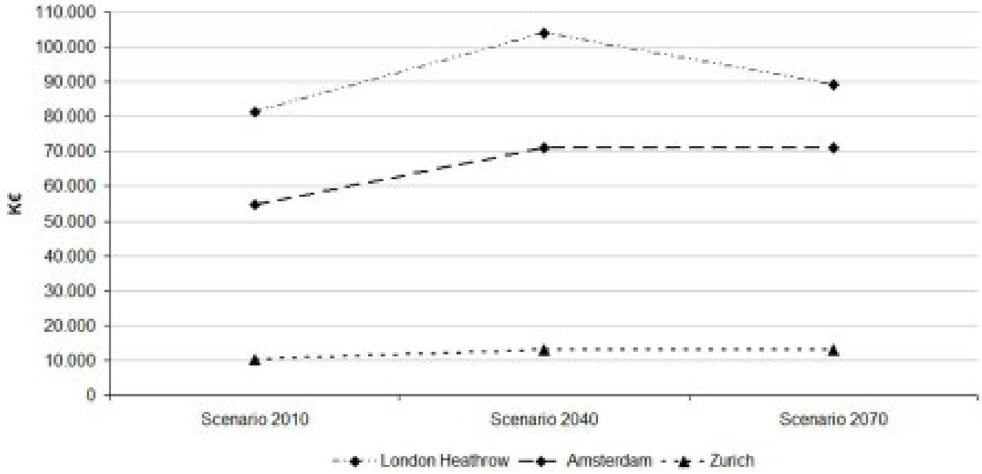

Figure 17 Average total daily social costs caused by extreme weather (Nokkala et al. 2012).

Valuation summary

The valuation summary is made difficult by the large number of transport modes and risks. In practice, there are a range of effects, some of which are positive (e.g. reduced winter impacts and potential accidents) and some negative (e.g. extreme heat).

Table 36 Valuation of I12. Risks to transport from high and low temperatures, high winds, lightning.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Medium to high	Medium to high	Medium to high	Medium to high	Medium to high	
Confidence		Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

In general, there are a set of no regret options in the form of improved weather and climate services, including early warning systems, for extreme risks for transport, which have been found to have high benefit to cost ratios across modes from the avoided damage and thus value of information (Clements et al., 2013[cccx]). There are further opportunities for these options, and general management of weather related risks through digital platforms, remote sensing, etc., and their use in real time network management (EEA, 2014[cccxi]), which can be considered no-regret because of the reduced costs of disruption and thus economic benefits in terms of travel time (ToPDAd, 2015[cccxii]).

The potential risks of high temperatures on the rail networks, and the potential economic costs of rail buckling risks under climate change have been previously estimated in the UK (e.g. Dobney et al., 2009[cccxiii], Alvater et al., 2012). The reactive adaptation response to these has been speed restrictions, although these have important travel time costs. There has been some analysis of the cost-effectiveness of options to address these risks, though these are mostly focused on improved risk assessment and monitoring (RSSB, 2016). There are potential rising risks from wind and vegetation growth, which are likely to mean increased vegetation management costs (which can be considered an impact or an adaptation).

There has also been analysis of the potential economic costs of heat on highways (including rutting and user delay costs, as well as additional capital maintenance costs) and the costs and benefits of addressing heat risks to highways (Atkins, 2013a). This considers technical surfacing options and found a modest positive net present value and cost-benefit ratio of slightly greater than 1. Alvater et al. (2012) also investigated the additional costs of using better asphalt for roads in the UK, and found the costs generally outweighed the benefits. There is also a large international literature in this area (from warmer countries), which highlight improved maintenance practices, risk assessments, early warning, and enhanced design standards for roads (e.g. EEA, 2014, Ecofys, 2016[cccxiv]). There are other approaches, e.g. with greater redundancy in road networks, but these involve significant extra costs. There is also emerging focus on focusing adaptation investments on the vulnerability hot spots on networks, i.e. to identify the points on the system where greater resilience would be most cost-effective (as part of network level analysis rather than for individual assets). While this has mostly focused on flooding (Oh et al., 2020[cccxv]), the same approaches could apply to other risks.

For existing infrastructure, improved monitoring and information, and also improvement of maintenance practices and operations, are considered low-regret adaptation options. For new infrastructure, there are opportunities for mainstreaming climate change adaptation into planning and design, to avoid retrofitting later. The balance of costs and benefits for such approaches depends on the costs, the timing and level of discounted future benefits, as well as the costs of retrofit later. This means some, but not all measures are likely to have positive NPVs and these may be site specific. There is the potential for decision making under uncertainty approaches for new transport infrastructure (e.g. considering flexibility, robustness, adaptive management) but these have important time and resource implications. The main risks of lock-in, and thus main role for such approaches, are for new roads, rail, etc. (rather than refurbishment or upgrades) due to siting decisions.

I13. Risks to digital from high and low temperatures, high winds, lightning

The CCRA3 Chapter 4 report identifies there are potential risks to digital, but that the evidence is low quality. There is a general understanding of the interactions between ICT infrastructure and weather, but less quantitative information on how climate change will affect the frequency and magnitude of these interruptions in the future, which makes it difficult to assess the exact level of risk to the sector. It also identifies that ICT is critical to the operation of wider infrastructure networks (infrastructure such as water, power and transport, are controlled over the telecommunications networks), business activities, and people, and underpins many critical services as well as wider communication. This means that outages can have significant impacts, including from interdependencies (see also Risk I1). Impacts can be asymmetric and vary by location. For example, rural locations, those at the end of a network line, or served by only one or two networks are most vulnerable to disruption.

<u>Valuation</u>
There is some older analysis of the potential impacts of climate change for the digital and ICT sector (Horrocks et al., 2010[cccxvi]). Climate change can impact directly on the ICT sector by damaging assets, increasing costs (operation and maintenance) and affecting revenues (Acclimatise, 2018[cccxvii]). These impacts can arise from different hazards, but notably floods, windstorms and extreme heat. In turn, disruption of digital and communications infrastructure can lead to cascading and indirect effects.

For the ICT sector, buildings and tower structures are the most vulnerable assets to extreme events. For example, cell phone towers are at risk from high wind speeds.

As outlined in I1, Pant et al. (2020[cccxviii]) investigated the economic impacts of failure events in the telecoms network, and estimated that direct losses for the top 50 events could vary between £0.22 – £3.6 million/day and total losses vary between £0.34 – £7.0 million/day.

Data centres are potentially vulnerable to high temperatures, but also to rapid fluctuations in temperature and humidity. Warmer temperatures are likely to mean higher cooling needs and thus energy costs for ICT. This is potentially important, because data centres are already significant energy consumers because of cooling demand. While estimates vary, there are anecdotal reports that around 2-3% of electricity use worldwide is consumed by data centres (BBC, 2016[cccxix]) and that the number of these centres might double (or treble) over future decades. It is possible to undertake a simple what-if analysis for the potential costs of this. McKinsey Global Institute (2020[cccxx]) report cooling costs for data centres, and report these can make up 40 percent of their total energy consumed. Total electricity demand in the UK was 346 TWh in 2019 (DUKES, 2020[cccxxi]). If we assume 2% of this is for data centres, and half of this is for cooling, then this is 3.46 TWh. This can be valued using the long-run variable costs of energy supply (LRVCs), see discussion in H6, and leads to an annual value of just over £300 million. Applying the increases in cooling demand days (again see H6) indicates that this impact could easily be tens of millions annually by the 2050s.

Related to this, ICT has a high dependency on electricity supply, and thus on potential power outages. The Ponemon Institute (2016[cccxxii]) – analysing data in the US - investigated the cost of (unplanned) data centre outages for 63 data centres. It reports that on average the cost of downtime is $740,357 per incident, which is equal to nearly $9,000 per minute (with a range from $926 – $17,244 per minute). These include direct costs account (36%), indirect costs (51%), and opportunity costs (12%). The majority of costs are from business disruption ($16.1 million for the 63 data centres), lost revenue ($13.1 million) and end-user productivity ($8.7 million). The report also estimates the average cost of outage by primary root cause of the incident: IT equipment failures result in the highest outage cost ($995,000), followed by cyber-crime. The least expensive cause was related to weather ($455,000). There are some case studies that demonstrate the potential costs of such events in operations or data centres, for example for airlines. In 2017, a power supply failure caused physical damage to British Airway's data centre, taking out the airline's IT systems (though the outage happened overseas): the company estimated the cost of this outage was more than £80 million, a figure which included compensation costs[cccxxiii]. Generally, the downtime costs will depend on the size of the business and small businesses will have a lower cost per minute. IDC (2015[cccxxiv]) estimated the downtime costs for small businesses the U.S. ranged between $82,200 and $256,000 for a single incident or $137 to $427 per minute. However, while it is clear that weather related events can have high costs, it is not clear how much these might increase with climate change.

Importantly, the cascading effects generated by failure in the ICT infrastructure can be significant. The interacting risks project (WSP, 2020) assessed those impacts that have a number of knock-on impacts and assessed which interactions were the most significant. Looking at upstream points of connection (nodes), the study found that although power supply interrupted is the node with the greatest number of downstream connections, this is followed by IT & comms disrupted. However, disruptions to IT & comms were found to contribute to the most significant risk pathways suggesting that these nodes are important drivers of overall risk (WSP, 2020). Looking at downstream nodes, travel and freight delayed has the greatest number of upstream connections across all three sectors (i.e. risks emanating in other sectors are more likely to impact this node). This point of connection also contributes to the most significant risk pathways suggesting that this node is an important contributor of overall risk.

The information available makes it difficult to estimate the potential magnitude of the economic costs of this risk. It is plausible that the increase in extremes, and higher temperatures, will have potentially important costs, and thus might indicate a medium or high level, but this is very preliminary

Table 37 Valuation of I13. Risks to digital from high and low temperatures, high winds, lightning.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Unknown	Medium	Medium	Medium	High	
Confidence		Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation
While there is some information on adaptation options for the digital and ICT sector (Horrocks et al., 2010), there does not appear to be a large literature on the costs and benefits of adaptation. There is a general low regret option to ensure better information on such risks, as well as to ensure climate risk assessment is included in design (and financial and economic appraisal, see also the supplementary Green book Guidance on accounting for climate change, Defra, 2020a). It is noted that the sector typically has short design lifetimes, and thus there is the potential to consider the management of some risks (e.g. equipment) as part of upgrades rather than through designing for future climates. However, there may still be cost-effective actions for critical digital infrastructure, given the cost of downtime from failures is often high; evidence from companies that report that the cost of downtime could be as high as £thousands per minute (Ponemon Institute, 2016).

Warmer temperatures are likely to mean higher cooling needs and associated energy costs (Lee et al., 2013[cccxxv]; Capozzoli and Primiceri, 2015[cccxxvi]; Song et al., 2015[cccxxvii]). There are a range of adaptation options from early warning and emergency planning through to back-ups to address heat extremes. These issues are linked to the general increase in cooling demand (see Chapter 5: Kovats and Brisley, 2021) and the potential role for energy efficiency standards.

The consideration of network risks, and more focused adaptation strategies to key vulnerabilities, can be a more efficient use of available adaptation resources. Adaptation can also be achieved by enhancing network redundancy and introducing back-ups. Pant et al. (2020) investigated the economic impacts of failure events in the telecoms network and estimated that direct losses for the top 50 events could vary between £220,000–£3.6 million/day and total losses vary between £0.34–£7.0 million/day. However, as the degrees of connections are increased, the economic impacts were found to decrease. The authors also show the benefits of introducing backup supply for the electricity sector in delaying and thereby decreasing the disruptions in the ICT sector by up to ~90% compared to a scenario with one connection and no back up (though note the study does not assess costs, and thus the overall economic net benefit).

It is also highlighted that ICT and digital solutions can help reduce risks or realise opportunities in other sectors, i.e. they have considerable potential as part of adaptation across many areas (ITU, 2014[cccxxviii]).

Summary of Risks and Opportunities for Infrastructure

The valuation results for the infrastructure theme are summarised below. The evidence for this theme is mixed. The most robustly quantified risk is associated with water supply (I5 but reported in H10), which draws on the detailed analysis in the CCRA3 Research reports as well as other studies. A demand/supply deficit is projected to occur in late-century (concentrated in England), with climate change being a key contributor alongside socio-economic change. This will lead to large economic costs, although there is less quantitative economic modelling to date (analysis has focused on physical modelling). Indicative analysis in this study suggests these costs will be high (£hundreds of millions/year), even considering existing adaptation in the water management plans, but further economic analysis is needed.

For approximately half of the infrastructure risks, there are some quantitative estimates, but these are taken from a wide range of studies, which are very inconsistent in terms of methods, climate scenarios, etc. This makes comparison difficult, and further, there is often a range of reported estimates between studies of the same risk (and in some cases, studies even report differences in the sign, depending on whether extremes are captured and if cold-related benefits are included). It also noted that many of the valuation studies are either highly aggregated (e.g. European scale including the UK) or local (i.e. case studies in a particular location), and there is a gap on robust national level estimates, with the water sector being the exception.

For the remaining risks and opportunities, there is not good quantitative information, either because the focus is on hazards that are uncertain (such as changes in the wind regime) or because there is little evidence in the literature. This makes valuation challenging. It is also highlighted that most studies focus on damage to infrastructure assets, and there is less information on how climate change will affect infrastructure services. Both are important to capture overall economic effects.

Based on the analysis undertaken, the most important risks in economic terms -alongside water (I5)- are estimated to be the risks of cascading risks (I1) and flooding to infrastructure directly (I2), both of which are considered to have potential economic costs of £billions/year.The economic costs of indirect/cascading impacts (I1) have been estimated as being between 1.3 to 3 times that of direct impacts of infrastructure failures depending on the approaches and models used, and the range of assumptions in the models. The main challenge is that there is no literature on how cascading risks might change with climate change, i.e. the scale of the increase. The recent WSP CCRA3 research study (2020), however, estimated an increase in overall cascading risk for a 2050 4°C scenario to be 5 – 6 times higher compared to the current baseline.

There is good information on the infrastructure assets at risk of flooding (I2), but less robust modelling of the potential annual damages and economic costs, especially as compared to modelling of flooding of buildings. Nonetheless, there is good evidence of the current economic costs of major flood years on infrastructure (including transport and electricity), which are found to be large, especially when indirect costs are taken account of, be this transport disruption (and lost travel time) or electricity outages. There is also quantitative analysis showing that flood hazards are projected to increase with climate change, and thus these costs are projected to rise.

There are also important risks to the energy sector (beyond flooding). While hydropower is a climate sensitive generation technology (I6), the low levels of hydro-power generation in the UK, and the potential for positive as well as negative effects of climate change, lead to a medium score. Indeed, some studies project potential benefits from changes in the average climate, though there are also projected negative effects from increasing variability. Wind power is also a climate sensitive generation technology (I10), and offshore wind will play a much larger share in electricity generation, as set out in recent Government commitments for 2030). Climate change has the potential to alter future wind regimes. The key problem, however, is that the projected changes in the average wind regime, as well as changes in the intensity, frequency and storms tract patterns for wind extremes, are very uncertain. While there are studies of the economic costs of climate change for the UK, these vary with the projections and scenarios used, and most report a range that includes potentially positive or negative outcomes. What is clear is that given the increasing size (and electricity generated) of the offshore wind industry, even small changes have the potential to have large economic costs or benefits (i.e. high or very high levels). In reality, it is likely that hydro-power and wind-power sectors face a mix of positive and negative effects, with potentially more positive outcomes for changes in the average climate, but more negative outcomes for changes in extremes, though these should not be aggregated because they require different adaptation responses.

The risks to other energy generation infrastructure are less clear. While there are potential impacts on thermal generation, with changes in thermal efficiency of current plants (I10) that could be high, or from changes to water availability (I9), the UK electricity mix is changing very rapidly due to the net zero commitment. There is a major evidence gap on how the risks to the energy sector will change as a result of this commitment, both for generation and end-use technology, but there are important potential risks (from both I9 and I10) from a move to gas and/or biomass coupled with carbon capture and storage, as well as an increase in the use of hydrogen generation. These issues are identified as a priority for further consideration, including for adaptation, because a very large new stock of technology will be added in the next 30 years that will operate in a period of future climate change.

Finally, there is much less information on the risks to the digital sector. Data centres are potentially vulnerable to extreme events such as floods as with other infrastructure, but they also have particularly vulnerability to warmer and peak temperatures, because of the need for mechanical cooling. The costs of cooling for the digital sector will clearly rise with climate change, and some indicative what-if analysis indicates the economic costs of these could be high (noting there are less opportunities for passive cooling, because temperature regulation is critical).

Table 38 Summary of Infrastructure theme valuation

Risk	Present Day	2050s, on a to pathway stabilising at 2°C by 2100*	2050s, on a pathway to 4°C at end of the century#	2080s, on a to pathway stabilising at 2°C by 2100*	2080s, for 4°C world at the end of the century#	Confidence
I1. Risks to infrastructure networks (water, energy, transport, ICT) from cascading failures	High	Very high	Very high	Very high	Very high	Low
I2. Risks to infrastructure services from river, surface water and groundwater flooding	High	High (possibly very high)	High (possibly very high)	High (possibly very high)	Very high	Low
I3. Risks to infrastructure services from coastal flooding and erosion	Unknown	Unknown (Possibly high)	Unknown (Possibly high)	Unknown (Possibly high)	Unknown (Possibly high)	Low
I4. Risks to bridges and pipelines from flooding and erosion	Medium	Medium	Medium	Medium	Medium	Low
I5. Risks to transport networks from slope and embankment failure	Medium	Medium-high	Medium-high	Medium-high	High	Low
I6. Risks to hydroelectric generation from low or high river flows	Low annualised but medium in high risk years	Medium (range varies from positive to negative)	Medium (range varies from positive to negative)	Medium range varies from positive to negative)	Medium (range varies from positive to negative)	Low
I7. Risks to subterranean and surface infrastructure from subsidence	Medium	Medium	Medium	Medium	Medium	Low
I8. Risks to public water supplies from reduced water availability	Medium	High	High	High	High	Low- medium
I9. Risks to energy generation from reduced water availability	Low	Unknown	Unknown	Unknown	Unknown	Low
I10. Risks to energy from high and low temperatures, high winds, lightning	Medium	High to very high (but potentially positive or negative)	High to very high (but potentially positive or negative)	High to very high (but potentially positive or negative)	High to very high (but potentially positive or negative)	Low
I11. Risks to offshore infrastructure from storms and high waves	Low	High (but could be positive or negative	High (but could be positive or negative	High (but could be positive or negative	High (but could be positive or negative	Low
I12. Risks to transport from high and low temperatures, high winds, lightning	Medium to high	Medium to high	Medium to high	Medium to high	Medium to high	Low
I13. Risks to digital from high and low temperatures, high winds, lightning	Unknown	Medium	Medium	Medium	High	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year.

Health, Communities and the Built Environment

The list of risks and opportunities considered in the CCRA3 Technical Report for Health, Communities and the Built Environment (Chapter 5) are shown below:

Risk or opportunity
H1. Risks to health and wellbeing from high temperatures
H2. Opportunities for health and wellbeing from higher temperatures
H3. Risks to people, communities and buildings from flooding
H4: Risks to the viability of coastal communities from sea level rise
H5: Risks to building fabric
H6: Risks and opportunities from summer and winter household energy demand
H7: Risks to health and wellbeing from changes in air quality
H8: Risks to health from vector-borne disease
H9: Risks to food safety and food security
H10: Risks to water quality and household water supplies
H11: Risks to cultural heritage
H12: Risks to health and social care delivery
H13: Risks to education and prison services

These risks and opportunities are some of the more well studied: they are discussed in turn below.

H1. Risks to health and wellbeing from high temperatures

CCRA3 Technical Report
Chapter 5 of the Technical Report highlights that high temperatures have a very wide range of health and social outcomes. This includes the effect of extreme heat (and heatwaves) on health (mortality and morbidity), and recent heatwaves have seen significant numbers of excess deaths, notably with 2,556 deaths in 2020. The chapter also outlines the risks of overheating in buildings, and reports that the rates of overheating in English dwellings are around 20%. There are also potential interactions identified between combined exposures from heat, air pollution, and wildfires. UKCP18 estimates that a "hot" summer such as 2018 current has historically had an annual probability of 10%, but this will increase to 50% (depending on the emissions scenario) by mid-century.

Valuation
The valuation has focused on the additional premature fatalities from high temperatures. There were major heatwaves in England in 2003 and 2006, which were both attributed with causing over excess 2000 fatalities (PHE, 2018a: 2018b[cccxxix]) and there have also been heatwaves in recent years, in 2016 (908 excess deaths), 2017 (778 excess deaths), and 2018 (863 excess deaths) (PHE, 2018c[cccxxx]) and 2,556 deaths in 2020. However, many heat-related excess deaths arise outside of heatwave events. Estimates suggest that there are around 2000 heat-related deaths per year, on average, in the UK (Hajat et al., 2014[cccxxxi]: Kovats and Osborn., 2016[cccxxxii]).

Hajat et al., (2014) estimated the increase in heat- related fatalities in the UK and these estimates can be used to look at valuation. Hajat et al., project fatalities rising from 2000 fatalities/year historically, to potentially 3000 per year by the 2020s, increasing to 5000 per year by the 2050s (climate only) or 7000 per year if population and age distribution changes are also considered (climate and socio-economic change), for a medium emission scenario. It also reported a significantly raised risk of heat-related mortality in all regions (and all devolved administrations). The Hajat study also considers uncertainty around this medium scenario, looking at nine models (but not scenario uncertainty, i.e. it did not consider 2 vs 4°C scenarios). These estimates were valued by Watkiss et al., 2019 and have been updated in this analysis. There are many caveats with these estimates. There are high uncertainties around future fatalities, and they may not fully capture future extreme temperature impacts or urban heat island effects, which might increase these impacts. However, they do not include the effects of natural acclimatisation or existing adaptation policy (including the Heatwave plan and HHWS), which would reduce these impacts, potentially significantly.

The economic impacts on human health are more difficult to value than many other sectors, because there are no observed market prices. However, it is possible to derive monetary values by considering the total impact on society's welfare. This requires analysis of three components which each capture different parts of the total effect (Hunt et al., 2016[cccxxxiii]):

- The resource costs i.e. medical treatment costs;
- The opportunity costs, in terms of lost productivity; and
- Dis-utility i.e. pain or suffering, concern and inconvenience to family and others.

The first two components can be captured relatively easily (as they are available from direct information and market prices). Techniques are also available to capture the third component, by assessing the 'willingness to pay' to avoid or the 'willingness to accept compensation' to tolerate the risk of a particular health outcome. These are derived using survey-based 'stated' preference methods and/or 'revealed' preferences methods that are based on observed expenditures such as on consumer safety. For this outcome, the key metric is the valuation of the change in risk of a fatality. This is commonly estimated through the metric of a Value of a Prevented Fatality (VPF), also known as the Value of a Statistical Life (VSL). Such an approach is already widely used in UK Government appraisal and cost-benefit analysis, for example in transport appraisal. In order to value these mortality effects in economic terms we adopt the unit value for a value of a prevented fatality, (VPF) that is used in transport appraisal by the Department for Transport (TAG databook, DFT, 2020[cccxxxiv]). This derives a value for prevention per fatality, based on the lost output, medical and ambulance costs, and human cost. The current value is £2,084,404 (2020).

The DFT guidance on the use of the VPF (DfT, 2019[cccxxxv]) also sets out that these health valuation endpoints (i.e. the VSL) should be increased in future years, as a result of changes in the value of lost output, medical costs and willingness to pay for reductions in risk of injury. Each element will change over time in line with the change in real average income, so it recommends values should be uplifted in line with forecast growth in real GDP per head. Similarly, for valuation of air pollution related mortality, Defra (2020[cccxxxvi]) recommends an uplift of 2% per year to reflect the assumption that willingness to pay for health outcomes will rise in line with real per capita GDP growth[11]. This significantly increases future unit values, though it is stressed that the use of these economic costs (with uplifts) in subsequent policy analysis, such as adaptation cost-benefit analysis, should undertake discounting of future values (HMT, 2020[cccxxxvii]), using social discount rates which are based on time preference and the wealth effect (the expected growth in per capita consumption over time).

However, there is some debate on the applicability of these VPF values to the heat and health context, because those affected include a large proportion of people that are old or have existing health conditions, and that may have lower life expectancy than the typical prevented fatality. Furthermore, the period of life lost – notably for heatwaves – may be small. This is often referred to as displaced mortality, i.e. the fatalities occur in those who have existing ill health and would have died anyway within a short period of time (also known as deaths brought forward). They would also not lead to the lost output associated with road causalities (lost output is an important proportion, around one third, of the VPF, the remainder being the human cost). There are different ways to address this. Quality of life is often used in health-related appraisal, which when combined with longevity, can be aggregated in the concept of a Quality Adjusted Life Years (QALY). QALYs are calculated by multiplying the change in QoL by the duration (in years) The current values in the Green Book are £60000 for a QALY (HMT, 2018) [2014 prices].

Similar issues to this exist in the air quality context, and previous studies in UK Government appraisal have addressed this by using a different approach, with the value of a life-year (VOLY). This was suggested by the Interdepartmental Group on Costs and Benefits (IGCB, 2007[cccxxxviii]), with values of

[11] The Green Book (2020) also states that for health 'Discounting of resources relating to health and life issues is carried out using the appropriate standard discount rate of 3.5% declining after 30 years. The value of VPFs, SLYs and QALY effects should be discounted at the health rate of 1.5%, declining after 30 years'. However, in this case, the vales should not be uplifted, because the assume of the rising WTP is already included (and thus using the 2% uplift and the 1.5% DR would be double counting).

£40,000 and £60,000 per VOLY used. These values could be transferred to the climate change related context (e.g. Watkiss and Hunt, 2012[cccxxxix]). However, this requires information on the average period of life lost from heat-related mortality and the quality of life lost, yet there is no robust evidence on the period of life lost. Previous studies in the heat related mortality context have used a number of different values, assuming on average a loss of life of 6 months, 1 year and 2 years (though it is noted that some individuals affected will lose a much greater period than this).). This is different from the value of a life year used in the mortality pathway.

It is stressed that there is considerable debate in the literature as to the relative merits of these different approaches, e.g. the VPF versus the VOLY or QALY metrics. Earlier best practice was to use both metrics (VPF and VOLY), at least in sensitivity analysis (Watkiss and Hunt, 2012). More recent evidence in the economics literature is shifting towards the use of the VPF only. For this study, we use both to illustrate the effect on the results. This is shown for the medium estimates from Hajat et al. This uses the DfT VPF and compares to a VOLY value, the latter assuming a value of £65,000 (2020 prices) and that 1 year of life is lost from those affected (note that is also broadly equivalent to the current QALY value). The analysis shows that the use of the full VPF leads to very high economic costs. These fall significantly with the use of the VOLY approach. Including the 2% uplift significantly increases the future values. It is stressed that these do not consider the existing heat-watch alert system (i.e. existing adaptation).

Table 39 The total economic costs of heat-related mortality from climate change and socio-economic change in the UK. £Million/year. 2020 prices, from estimates of Hajat et al., 2014. Note does not include current adaptation. Medium values.

Value of a Prevented Fatality (VPF)	**Central estimates of £Million / year - total**			
Time period	**2000-2009**	**2020s**	**2050s**	**2080s**
heat- present day	**4,115**			
heat projection - climate only		**6,007**	**11,068**	**17,651**
heat projection - climate and population growth/age		**6,839**	**14,674**	**26,134**
Sensitivity VPF with 2% uplift	Central estimates of £Million / year			
heat- present day	4115			
heat projection - climate only		8,412	23,029	66,523
heat projection - climate and population growth/age		9,576	30,532	98,497
Sensitivity VOLY (1 year)	Central estimates of £Million / year			
heat- present day	128			
heat projection - climate only		187	345	550
heat projection - climate and population growth/age		213	458	815
Sensitivity VOLY (1 year) with 2% uplift	Central estimates of £Million / year			
heat- present day	128			
heat projection - climate only		262	718	2,074
heat projection - climate and population growth/age		299	952	3,072

The range of values from Hajat is used to provide a low, central and high value (which is a very approximate proxy for 2° and 4°C[12]). This is shown for the combined total of climate and socio-economic change below, for the VPF only (current and constant, no uplift). It is stressed these values do not include current adaptation.

[12] Strictly speaking, the subset of nine regional climate model variants in the Hajat paper are cited as climate sensitivity in the range of 2.6–4.9°C.

Table 40 The total economic costs of heat-related mortality from climate change and socio-economic change in the UK. £Million/year. 2020 prices, no GDP uplift, from estimates of Hajat et al., 2014 for low, central and high climate change. Note does not include current adaptation.

Value of a Prevented Fatality (VPF)	**Mean estimates of £Million / year - total**			
Time period	**Baseline**	**2020s**	**2050s**	**2080s**
Present day	**4,115**			
Low climate scenario		3419	6503	13814
Medium climate scenario		6839	14674	26134
High climate scenario		11113	28014	40135

There is also some analysis of the impacts by Devolved Administrations in the Hajat paper. These report incidence rates (deaths per 100,000 people each year) as below. These show higher incidence rates for England and Wales, although there are still major increases in rates for the 2050s and 2080s in Scotland and Northern Ireland. New analysis has been undertaken here to estimate the economic costs per DA using the same approaches as above.

Table 41 The mean, minimum and maximum estimates of heat-related deaths in regions/year/100000 population of all ages. Source Hajat et al., 2014.

	2000			**2020**			**2050**			**2080**		
	Mean	Min	Max	**Mean**	Min	Max	**Mean**	Min	Max	**Mean**	Min	Max
UK	3.3	0.9	6	**4.8**	2.4	7.8	**8.8**	3.9	16.8	**14**	7.4	21.5
N.Ireland	0.9	0.3	2.3	**1.6**	0.6	2.6	**2.9**	1.5	6.1	**4.9**	2.9	7.2
Scotland	0.7	0.2	1.5	**1.3**	0.3	2.2	**2.4**	1.3	5.2	**4.4**	2.6	7.2
Wales	2.4	0.7	5.7	**3.5**	1.6	5.8	**6.5**	3.1	14.3	**10.6**	5.3	16.2

Table 42 The total economic costs of heat-related mortality from climate change and socio-economic change by DA, valued using VPF. £Million/year. 2020 prices, no GDP uplift, from estimates of Hajat et al., 2014 for medium climate change. Note does not include current adaptation. Mean values, Medium climate.

Value of a Prevented Fatality (VPF)	**Central estimates of £Million / year – total – climate + socio-economic change**			
Time period	**Baseline**	**2020s**	**2050s**	**2080s**
UK	**4,115**	6839	14674	26134
England		6387	13698	24269
Northern Ireland		65	137	259
Scotland		151	327	672
Wales		235	512	934

The additional cases of heat-related morbidity (i.e. hospital admissions) would add to these costs, potentially significantly. The analysis has used the approach adopted in previous studies for CCRA (Hames and Vardoulakis, 2011[cccxl]) which estimates the increase in hospital patient days using a ratio of mortality: morbidity of 1:102. The main problem is the severity of these admissions is not fully known. An upper value can be derived based on the WTP values for respiratory hospital admission / cardiovascular admission, as applied in the air pollution context (Defra, 2019). A lower value is based on unit value of £700 per case, as used in the first UK Climate Change Risk Assessment (Hames and Vardoulakis, 2012), updated to 2020 prices. The resulting estimates are below. These significantly increase the overall impacts. These impacts would increase with the use of the 2% uplift, and would have similar profile across the DAs to the mortality numbers.

Table 43 The total costs of heat-related morbidity in the UK. 2020 prices / values. £Million/year. 2020 prices, no GDP uplift, from estimates of Hajat et al., 2014 for medium climate change. Note does not include current adaptation.

	Central estimates of £Million / year - total			
Low valuation (hospital case)	**Baseline**	**2020s**	**2050s**	**2080s**
heat- present day	141	0	0	0
heat projection - climate only	0	206	379	605
heat projection - climate and population growth	0	234	503	895
High valuation (respiratory hospital admission)	**Baseline**	**2020s**	**2050s**	**2080s**
heat- present day	1711	0	0	0
heat projection - climate only	0	2499	4604	7342
heat projection - climate and population growth	0	2845	6104	10870

It is highlighted there is considerable uncertainty around the projections of climate change, the projected functions for estimating fatalities (impacts) and the valuation. A sensitivity testing (Watkiss and Hunt, 2012) found these uncertainties can change the results by two orders of magnitude. It very difficult to project robust central estimates, though a key conclusion is that in all cases, the economic costs are projected to be significant. The assumptions made on acclimatisation (the natural adaptation in physiological terms and through behaviour over time to changing temperatures) and existing adaptation (notably existing heat alert systems and plans) are also likely to have a major influence on impacts as well.

There are also an additional set of impacts on well-being from higher temperatures. These are associated with indoor overheating and discomfort. These involve cases where a physical endpoint does not result (morbidity or mortality) but there are impacts on comfort levels. However, these are potentially captured in the estimated cooling estimates in H6 and are not included here to avoid double counting. In effect, there will either be more discomfort from higher temperature in homes and buildings, or higher air conditioning use for cooling, but it is double counting to include both. The additional costs of air conditioning can be taken as a proxy for the welfare impact of discomfort (especially as the review has not found WTP studies to avoid discomfort).

The summary of valuation estimates is presented below. There is reasonable evidence at the UK level for the magnitude ranking, but the very high uncertainty on impacts and valuation, including acclimatisation effects and existing adaptation, and thus a low-medium confidence is assigned.

Table 44 Valuation of H1. Risks to health and wellbeing from high temperatures. No adaptation (including current adaptation) included.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Very high	Very high	Very high	Very high	Very high	Very high
England	Very high	Very high	Very high	Very high	Very high	Very high
N. Ireland	Medium	High	High	High	High	High
Scotland	High	High	High	High	High	Very high
Wales	High	High	High	High	High	High
Confidence	Low - Medium	Low - Medium	Low - Medium	Low - Medium	Low - Medium	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation
The quantified benefits and costs of addressing overheating in buildings involves a range of assumptions about mortality risks associated with overheating.

Several studies have compared the costs of mechanical vs. passive methods of space cooling in new houses and retrofits (Frontier Economics, 2013[cccxli]; Adaptation Sub-Commitee, 2014[cccxlii]; Wood Plc (2019[cccxliii]). These generally report positive benefit to cost ratios or high cost-effectiveness (£ / % reduction in temperature). This indicates the potential for low regret options but also that there is a need (and opportunity) to address further risks in climate smart design to address lock-in risks and co-benefits.

This is a complex area to assess costs (to households) given the multiple co-benefits and potential harms for each housing intervention. No-cost options to manage overheating can be effective to some extent, such as utilising increased natural ventilation (opening windows), using existing blinds and curtains during the day to limit heat gain and changing behaviours. Shading is the most cost-effective option for cooling houses (Wood Plc, 2019). Many low-carbon retrofit options share commonalities with adaptation options and so could potentially share the cost and reduce overall costs.

There is also analysis of the benefits and costs of heatwave warning systems. There is some evidence on the benefits of heat alert systems for reducing urban heat fatalities internationally which indicates very high BCRs (e.g. Ebi et al., 2004[cccxliv]; Toloo et al, 2013[cccxlv]). There is currently no published data on the costs and benefits of the Heatwave Plan and HHWS in England, although an evaluation led by PHE is expected to be published soon. However, there has been economic analysis of the potential BCRs of other HHWS, and how these will change with climate change, that takes account of rising benefits but also rising resource costs. Hunt et al., (2016cccxlvi) estimated a baseline BCR of 11:1 from the HHWS for London currently, and found that this increased under climate change (depending on the scenario, to between 21:1 to 28:1). Similar BCRs are also reported for heat alert warning in studies across Europe (UBA, 2012[cccxlvii]; Bouwer et al., 2018[cccxlviii]; Chiabai et al., 2018[cccxlix]). The values are site- and context-specific, but BCRs also depend critically on the valuation of avoided fatalities, and whether this uses a Value of Statistical Life, (VSL), or some form of adjustment (e.g. Value of Life Year Lost or Quality Adjusted Life Years) – use of VSL considerably increase the BCRs. There are other related measures that extend HHWS to target health related mortality as part of heatwave plans, that include supporting interventions in the health and social care sectors: initial reviews of these find they also offer potentially high benefit to cost ratios (Pohl et al., 2014[cccl]; Watkiss et al., 2019[cccli]) there

The studies assume that the cost of operating the warning system increases under future climate change, but this may not be the case as the health system response may become more efficient, and the costs to the provider (e.g. the Met Office) are assumed to be fixed. As discussed above, the heat alert systems alone do not fully manage the health risk in the population (Watkiss et al., 2019[ccclii])

H2. Opportunities for health and wellbeing from higher temperatures

CCRA3 Technical Report
Chapter 5 of the Technical Report sets out that there are potential benefits from warmer winters for cold-related mortality, although some of these will be offset (in absolute terms) by demographic changes and the higher number of older people in the population in future year. Cold related mortality is important in excess deaths, but there are challenges in separating out cold from other winter factors. It also sets out that there are physical and mental health benefits of increased physical activity, but there is limited evidence on the extent to which a warmer climate will increases these activities.

Valuation
Climate change will also reduce future cold-related mortality. Earlier studies (Watkiss and Hunt, 2012) quantified and valued the cold related benefits for the UK: these results indicated that the change in cold related fatalities (benefits) from climate change were probably larger than the additional heat

related impacts (see risk H1). In CCRA1, indicative analysis also suggested the economic benefits of falls in cold related mortality would be larger than the costs of heat related mortality (Hames et al., 2012). However, an update for CCRA2 found lower relative reductions in cold related cases than the increase in heat-related fatalities by late century (Hajat et al., 2014).

For this analysis we use the values from Hajat et al., (2014). This study estimates baseline numbers of cold related fatalities at approximately 40,000/year in the UK, which is much higher than for heat (which is only 2000/year). The estimated change in future cold related fatalities from climate change is complex, however, because of socio-economic change. Hajat et al. project that cold-related mortality could increase in the 2020s due to increasing population at risk and changes in the age distribution of people (i.e. the combined effect of climate and socio-economic change), but then decrease in later years.

These results have been valued below, using the same methodological approach to valuation set out for H1, however, they only show the change from climate change and do not include baseline numbers (of cold related deaths), so are not directly comparable to H1 (where baseline estimates are included). Note that the change due to climate alone (when socio-economic change is excluded) would be positive in all periods, and would also be much higher (around three times higher than the combined influence of climate and socio-economic together), because the rise in benefits from warmer temperature is reduced due to socio-economic change.

Table 45 The marginal economic costs of cold related mortality UK. Increase over baseline. 2019 prices and value. Central estimate. Based on estimates from Hajat et al, 2014.

Value of a Prevented Fatality	**Central estimates of £Million / year**			
Time period		**2020s**	**2050s**	**2080s**
cold projection - climate and population growth		-2,989	+ 2,107	+ 10,218
Sensitivity Value of Life year Lost (1 year)				
cold projection - climate and population growth		-93	+66	+ 319
VPF With 2% uplift				
cold projection - climate and population growth		-4,185	+ 4,385	+ 38,509
QALY With 2% uplift				
cold projection - climate and population growth		-131	+137	+ 1,201

There is also some analysis of the impacts by Devolved Administration in the Hajat paper. These report incidence rates (deaths per 100,000 people each year) as below. These show higher incidence rates for Wales in particular, although there are still major increases in rates for the 2050s and 2080s in Scotland and Northern Ireland.

Table 46 The mean, minimum and maximum estimates of cold-related deaths in regions/year/100000 population of all ages. Source Hajat et al., 2014.

	2000			**2020**			**2050**			**2080**		
	Mean	Min	Max	**Mean**	Min	Max	**Mean**	Min	Max	**Mean**	Min	Max
UK	83.9	73.7	101.8	76.1	69.4	95.5	61.1	54.5	75.1	48.7	31.9	69.3
N.Ireland	68.7	59.4	82.5	62.3	57.1	76.4	50.6	45.7	61	40.9	28.2	56
Scotland	46.7	40.3	59.4	41.5	35.5	55	34.1	29.2	43.6	26.5	16.6	39.1
Wales	55.6	48.2	71.9	49.3	42.4	66.3	40.8	34.3	53.5	31.2	19.8	46.4

Table 47 The marginal economic costs of cold-related mortality from climate change and socio-economic change by DA, valued using VPF. £Million/year. 2020 prices, no GDP growth, from estimates of Hajat et al., 2014 for medium climate change. Note does not include current adaptation. Mean values, Medium climate.

Value of a Prevented Fatality (VPF)	Mean estimates of £Million / year - total			
Time period		**2020s**	**2050s**	**2080s**
UK		-2989	+2107	+10218
England		-2726	+1717	+8288
Northern Ireland		-23	+55	+266
Scotland		-67	+160	+966
Wales		-173	+176	+699

In addition to these benefits, there would also be a large benefit from reduced cold related morbidity which again, would be large. There is not good information on these benefits, and thus valuation is not possible. It is highlighted that this could include a wider set of events than cold related morbidity including reduced trips and falls on ice.

There is also likely to be a large recreational benefit from warmer average temperatures. The UK Natural Capital Accounts (ONS, 2019[ccclii]) present estimates for current recreational and aesthetic benefits. Recreation is valued in the accounts at an average of £8.5 billion/year over the past decade. The ONS reports that overall the average length of an outdoor recreation visit in the UK was two hours and 10 minutes (including travel). The accounts also measure recreation by looking at surveys that capture recreational values in the housing market by looking at the willingness to pay for living close to green and blue spaces, though this is less relevant as there is no obvious link between climate change and changes in recreational space.

Climate change – through average warmer temperatures - has the potential to increase the demand for (outdoor) recreation, which in turn will generate potential health benefits. There are studies that look at future changes in the UK's climate and project benefits in terms of higher amenity value (e.g. Maddison (2003) and Maddison and Rehdanz (2011)[cccliv]). However, there is no information on how much climate change might increase recreation, to then allow the estimation of subsequent health benefits. If such estimates were available, then valuation would be possible using the approaches used in the ONS accounts and White et al., (2016) to estimate the cardio-vascular and other benefits from outdoor activity.

The summary of valuation estimates is presented below. There is reasonable evidence at the UK level for the magnitude ranking, but the very high uncertainty on exact impacts and valuation, means that a low-medium confidence is assigned.

Table 48 Valuation of H2. Opportunities (benefits) for health and wellbeing from higher temperatures.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Very high	+Very high	+Very high	+Very high	+Very high	
England	Very high	+Very high	+Very high	+Very high	+Very high	
N. Ireland	Very high	+Medium	+Medium	+High	+High	
Scotland	Very high	+High	+High	+High	+Very high	
Wales	Very high	+High	+High	+High	+Very high	
Confidence	Medium	Low- medium	Low- medium	Low- medium	Low- medium	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation
There is little information on the costs and benefits involved in additional interventions to help address opportunities for health and well-being, but there is likely to be the potential for low-regret and low-cost interventions to help raise awareness and ensure opportunities are fully realised. There are well established interventions for public health communication and awareness raising, which have low costs, although these have largely been targeted at impacts rather than opportunities in the health and adaptation domain to date. Interventions to enhance opportunities could lead to large economic benefits (Hunt et al., 2016[ccclv]), in terms of societal welfare from three components: lower resource costs i.e. avoided medical treatment costs; increased opportunity costs from gains in productivity; and the avoided dis-utility i.e. pain or suffering, concern and inconvenience to family and others. A no-regret option would be to investigate these potential benefits, and look at the possible interventions to help deliver these.

H3. Risks to people, communities and buildings from flooding

CCRA3 Technical Report
Chapter 5 of the Technical Report assesses the risk of flooding as one of the most severe risk from climate hazards for the UK population – both now and in the future. The magnitude of the risk has possibly increased since the last assessment report, although so has the adaptation response. It reports that the risk of flooding from rivers is the dominant source, but assuming that current levels of adaptation continue, surface water and coastal risks increase their relative contribution to UK flood risk [note this is subject to assumptions about socio-economic growth, see valuation below]. Groundwater has a limited contribution at national scale, although will be important locally.

Valuation
Floods are one of the most important weather-related loss events in the UK and have large economic impacts, as reported in recent severe flooding events. These events lead to tangible direct damage such as physical damage to buildings, but also intangible direct impacts in non-market sectors (such as health). They also lead to indirect impacts to the economy, such as transport or electricity disruption, and major events can have macro-economic impacts. For example, Brown et al. (2013[ccclvi]), using data of approximately 180 nations, found that for every 1% increase in the area of a country experiencing severe rainfall, the GDP falls by around 1.8%.

There are large reported costs to residential properties from recent flood events. The Environment Agency estimated the costs of recent floods. The estimate of damage for residential property damage was £1,500 million for the summer 2007 floods, £320 million for the 2013-2014 winter floods and £350 million for the 2015 to 2016 winter floods.

Looking to future climate impacts, there is a relatively good evidence on the future effects of climate change in terms of the direct impacts from the national level analysis of floods, notably the CCRA2 and CCRA3 research projects (Sayers et al., 2017[ccclvii]: Sayers et al., 2020[ccclviii]). The expected annual direct damages for residential properties from all sources of flooding by UK country from these two studies are shown below.

The 2017 Sayers study is shown first below, showing the Expected Annual Damage (EAD), which is the mean economic damage over all possible flood return periods (averaging small damages from frequent flood events and large damages from rare events). Note this shows all flooding, including coastal, as well as river. However, it only includes direct damage losses, it does not cover the other issues with flooding, e.g. health and well-being impacts. It also assumes a static socio-economic scenario, i.e. there is no economic growth or increase in residential properties assumed. Current EAD for residential properties was estimated at £340 million per year EAD. Looking at flooding from all sources, with current levels of protection maintained, These values were projected to increase significantly by the 2080s. The projected increases are 50% under the 2°C climate change projection, 150% under 4°C climate change projection, and six fold under the H++ scenario (a high end scenario) – with the largest % increases from coastal flooding. Note, however, that these estimates do not factor in socio-economic change. When projections of population growth are included, the risks increase, as shown by the inclusion of population (see final rows).

Table 49 Economic costs of ALL flooding in the UK. Climate change only. No discounting, no adaptation. Sayers et al 2017. Million £ per year. Only population growth (not per capita GDP).

No			**2020s**			**2050s**			**2080s**	
EAD (£ million))	**Current**	**2°C**	**4°C**	**H++**	**2°C**	**4°C**	**H++**	**2°C**	**4°C**	**H++**
Residential only (direct only)	340	364	459	585	428	619	1,292	513	918	2,448
Residential with low pop. growth	*340*	*388*	*486*		*476*	*663*		*561*	*952*	

The 2020 Sayers study for CCRA3 updates these figures. The analysis includes three scenarios, which allow the analysis of different levels of adaptation:

- Reduced whole system adaptation (RWS), i.e. no additional adaptation. This is a counterfactual scenario with low levels of adaptation, assuming that existing flood protection is maintained but implementation is in-line with a lower level of ambition, i.e. investment in conventional defences fails to keep pace with climate change.
- Current objectives and current adaptation (CLA). This assumes flood risk management policies continue to be implemented as in the recent past whilst taking on board anticipated changes that are likely to result from recent changes in policy.
- Enhanced whole system adaptation (EWS). This goes beyond the current implementation of policy (and recently introduced policy) with implementation in-line with a higher level of ambition.

The total present day expected annual direct damages to residential properties from all sources of flooding in the UK is estimated at £255 million for fluvial (river), £139 million for surface and £82 million for coastal flooding, giving a total of £476 million. The breakdown by DA of expected annual damage (direct) is shown below. Note other studies report different baseline numbers, as highlighted in the CCRA3 Technical Report, including at the DA level.

Table 50 Current Expected annual damage (£Million) flooding for residential (direct only) by DA. Source Sayers et al. (2020).

	EAD (£Million)			
	Fluvial	**Surface**	**Coastal**	**TOTAL**
UK	254.8	138.7	82.0	475.5
England	172.0	59.8	59.5	291.3
N. Ireland	6.9	14.1	0.2	21.2
Scotland	44.3	17.8	6.4	68.5
Wales	31.6	46.9	16.0	94.5

The Sayers study also projects the change in future flood risk. These are shown for river and surface, and separately for coastal floods, below, broken down by DA, for the current adaptation scenario. These values include population growth only. The values show the average of the low and high population projections. It is stressed that these values assume population increases, but otherwise a static socio-economic scenario, i.e. there is no economic growth or increase in residential properties or value at risk.

Table 51 Expected annual damage (EAD) for residential properties (direct) from coastal flooding under different climate scenarios (£ and % increase relative to present day, average population growth, no economic change, current level of adaptation) (Source: Sayers et al. 2020)

EAD £Million		2050		2080	
	Present day	2°C	4°C	2°C	4°C
UK	82.0	137.6	184.3	192.7	296.0
		68%	125%	135%	261%
England	59.5	113.8	157.3	166.1	261.9
		91%	165%	179%	341%
Northern Ireland	0.2	0.3	0.5	0.4	0.7
		69%	204%	156%	348%
Scotland	6.4	7.2	7.9	7.4	8.4
		13%	24%	16%	31%
Wales	16.0	16.3	18.6	18.8	25.0
		2%	16%	17%	56%

Table 52 Expected annual damage (EAD, £million) for residential properties (direct) from fluvial and surface water flooding under different climate scenarios (£ and % increase relative to present day, average population growth, no economic change, current level of adaptation) (Source: Sayers et al. 2020).

EAD			2050		2080	
£Million		Present day	2°C	4°C	2°C	4°C
UK	Fluvial	254.8	317.0	384.9	322.1	451.8
			24%	51%	26%	77%
	Surface	138.7	209.7	255.6	242.1	325.4
			51%	84%	75%	135%
	Total	393.5	526.7	640.6	564.2	777.2
			34%	63%	43%	98%
England	Fluvial	172.0	229.9	278.6	235.3	333.0
			34%	62%	37%	94%
	Surface	59.8	92.9	118.1	110.3	159.3
			55%	97%	84%	166%
	Total	231.8	322.8	396.7	345.6	492.4
			39%	71%	49%	112%
N. Ireland	Fluvial	6.9	7.2	8.6	7.7	10.1
			4%	24%	11%	46%
	Surface	14.1	23.6	28.3	26.9	35.0
			67%	100%	90%	147%
	Total	21.1	30.9	36.9	34.6	45.1
			46%	75%	64%	114%
Scotland	Fluvial	44.3	44.7	59.1	44.5	66.2
			1%	33%	0%	49%
	Surface	17.8	30.6	37.3	34.8	45.0
			72%	110%	95%	153%
	Total	62.1	75.3	96.4	79.3	111.2
			21%	55%	28%	79%
Wales	Fluvial	31.6	35.2	38.6	34.5	42.4
			12%	22%	9%	34%
	Surface	46.9	62.5	71.9	70.2	86.1
			33%	53%	50%	84%
	Total	78.4	97.7	110.6	104.7	128.5
			25%	41%	33%	64%

The total values for all floods on residential properties (coastal, river and surface) are shown below. Values for the reduced adaptation and whole adaptation scenarios are also shown for comparison.

Table 53 Expected annual damage (EAD) for residential properties (direct) from ALL flooding under different climate scenarios (£ and % increase relative to present day, average population, no economic change, three scenarios) (Source: Sayers et al. 2020).

Current Level of Adaptation

		2050		2080	
EAD (£Million)	**Present day**	**2°C**	**4°C**	**2°C**	**4°C**
UK	475.5	664.3	824.9	757.0	1,073.2
England	291.3	436.6	554.0	511.8	754.3
Northern Ireland	21.2	31.1	37.4	35.0	45.8
Scotland	68.5	82.6	104.3	86.7	119.5
Wales	94.5	114.0	129.2	123.5	153.5

No additional action (RWS)

EAD (£Million)		**2050**		**2080**	
	Present day	**2°C**	**4°C**	**2°C**	**4°C**
UK	475.5	806.6	949.5	979.3	1,334.8
England	291.3	548.7	654.2	691.6	969.7
Northern Ireland	21.2	33.2	39.2	37.9	49.4
Scotland	68.5	98.9	114.4	109.9	141.4
Wales	94.5	125.8	141.7	139.9	174.2

Enhanced whole system adaptation (EWS)

EAD		**2050**		**2080**	
£Million	**Present day**	**2°C**	**4°C**	**2°C**	**4°C**
UK	475.5	585.9	674.2	643.2	844.2
England	291.3	376.7	437.4	423.4	572.1
Northern Ireland	21.2	29.8	35.0	32.3	41.3
Scotland	68.5	70.3	80.2	72.2	89.7
Wales	94.5	109.2	121.6	115.3	141.1

As well as the direct damages, floods lead to indirect damages. The Sayers report assumes these are 70% of the direct (residential) damages plus intangibles assumed to be an additional 20% of the direct (residential) damages. However, no detailed explanation is given in the report about the choice of such uplift, and what it captures exactly. Nevertheless, this means the figures above could be 90% larger when indirect damages are included. Further, Sayers study does not take economic growth into account.

There are alternative estimates of future flood costs in the Environment Agency's Long-term Investment Strategy (2019) and at DA level for equivalent analysis, such as with the SEPA analysis.

It is also stressed that there is considerable uncertainty around these projected future numbers, from the climate model projections (noting the values above do not communicate climate model uncertainty, only scenario uncertainty), but also from further uncertainties around the hydrological models used. This uncertainty can be very large. For example, previous European flood studies e.g. Rojas et al. (2013[ccclix]) find very large variation in the flood hazard change for the UK, even for the same scenario, when different regional climate model outputs are used. This found that the river flood damages could vary by a factor of two, from the choice of the regional climate model even for the same scenario. This study also reported that the UK has one of the highest flood related damage costs from climate change in all of Europe.

Other studies provide different numbers for the UK. Rojas et al. (2013) estimated river flooding alone would increase to a total of €7.8 billion/year (2050s) and €20.4 billion/year (2080s) for A1B scenario in the UK (average ensemble value, climate and socio-economic change): these are equivalent to 0.22% and 0.35% of GDP. This is significantly higher than the Sayers et al values. Roudier et al. (IMPACT2C, 2015) estimated the EAD from climate change will rise in the UK from €0.25 billion/year currently to €1.78 billion (climate only) to €3.49 billion (climate and SSP2) for a 2°C scenario. These include residential and non-residential floods, but are for rivers floods only, and again are much larger than from the Sayers analysis. In particular, higher values are estimated when future economic change is considered (Sayers et al assume higher population in the future, but no other socio-economic change).

Similarly, for coastal flooding, Brown et al. (2015[ccclx]) used the DIVA model and found much higher impacts for the UK. They find costs rise rapidly by the late century, especially for higher emissions pathways. They also find a large influence of socio-economic changes, which grows late century, and leads to extraordinarily high costs in late century for high sea level rise scenarios. However, it is stressed that a large part of this increase is driven by the socio-economics (acting together with the change in hazards) - in the absence of socio-economic change, damages in the 2080s (RCP45) in the UK were estimated to be Euro 5 billion/year, rather than Euro 21 billion/year with both climate and socio-economic change. Note that the study found that the UK has one of the highest coastal damage in Europe, because of higher storm surge risks in the North Sea.

Table 54 Economic costs of coastal flooding in the UK. Climate change and SSP2. 2010 Prices, no discounting, no adaptation. Brown et al 2015. Million Euros per year. Central and low to high SLR.

	2020s (2016-2040)	**2050s (2040-2070)**	**2080s (2071-2100)**
RCP2.6	€309 million *(275L to 482 H)*	€1823 million *(1380L to 5298H)*	€9287 million *(5420L to 37880H)*
RCP4.5	€316 million *(284L to 480H)*	€2279 million *(1637L to 7855H)*	€21713 million *(12111L to 77376H)*
RCP8.5	€432 million *(384L to 702H)*	€5776 million *(3868L to 19943H)*	€74256 million *(49700L to 156414H)*

Most recently, the PESETA IV study has assessed the potential economic costs from river flooding (Dottori et al., 2020[ccclxi]) and for coastal flooding (Vousdoukas et al., 2020[ccclxii]) for Europe, providing specific UK values. Again, these report much higher values than Sayers. This is partly because they include residential and non-residential damages, but also because of socio-economic assumptions. For river flooding, the analysis estimated EAD at billions late century, again finding that the UK was one of the more affected countries in Europe (though several others are higher). For coastal flooding, the UK ranks second highest in terms of economic costs in Europe (after France). Similar findings are reported in the COACCH study, which also identifies much higher damage costs from coastal flooding for the UK.

Table 55 Expected annual damage (in €million, 2015 values) under present conditions (base), future socioeconomic conditions (2050 and 2100 economy) and climate scenarios (1.5°C, 2°C, 3°C warming).

		EAD Base economy			EAD Economy 2050		EAD Economy 2100		
Country	base	1.5°C	2.0°C	3.0°C	1.5°C	2.0°C	1.5°C	2.0°C	3.0°C
UK	642	1066	1419	2391	1358	1818	2277	3073	4991

Table 56 Expected Annual Damage (EAD, in €billion) from coastal flooding in 2050 and 2100 under moderate mitigation and high emissions scenarios for the UK. Vousdoukas et al., 2020.

		Moderate emissions		High emission	
COUNTRY	**Baseline**	**2050**	**2100**	**2050**	**2100**
UK	0.4	2.5	20.2	3.2	39.1

The PESETA values have also been put into an economic modelling framework (Szewczyk et al. 2020[ccclxiii]) to identify welfare losses. The results are shown below. Note that these include values for all of UK and Ireland.

Table 57 Welfare losses from river and coastal flooding (bn € and % of GDP) for the three climate scenarios; the losses reflect damage from warming additional to any current losses. No adaptation.

	Welfare (bn €)			Welfare (% of GDP)		
	1.5°C	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
River flood UK & Ireland	-0.6	-1.0	-2.3	-0.03	-0.05	-0.12
Coastal flood UK & Ireland	-0.7	-1.4	-5.2	-0.04	-0.07	-0.27

One consistent reason these values are higher is because they consider socio-economic change in terms of economic growth as well as population growth. The Sayers CCRA3 analysis does consider the increase in number of properties based on a population uplift, but it does not include economic growth[13]. This will significantly underestimate the impact of climate change because in reality the increased flood hazards with climate change will act on a higher value at risk.

The Defra (2020[ccclxiv]) and EA (2010[ccclxv]) guidance on flood appraisal is not specific on what to do when estimating future benefits, although it does provide guidance on future costs (stating that future values should be taken as existing values unless there are good reasons to do otherwise). Standard practice in other Government appraisal is to increase the intangible elements of economic values over time, for example, the value of fatalities, or environmental damage, re uplifted in line with forecast growth in real per capita GDP growth (DfT, 20190[ccclxvi]). In terms of the willingness to pay of people to avoid floods, this might also be assumed to increase with income over time in line with real GDP growth per head. Similarly, in terms of contents of properties affected by flooding, the value at risk would be expected to increase over time. However, it is less clear if the costs of repair (following floods) would rise, indeed, it might be more typical in appraisal to assume it does not. This might infer that some of the values should be increased while others are held constant, but this would make analysis complicated.

To explore the general influence of socio-economic growth, and thus its potential impact, we have undertaken a sensitivity analysis by building in an uplift based on economic growth and applying this to the Sayers et al. 2020 analysis. A central GDP/per capita (central population) multiplier uplift has been constructed by dividing GDP (central) projections by populations projections (also central). The factor multipliers for the years 2055 and 2085 have been applied to EAD figures for 2050s and 2080s respectively. This dramatically increases the Sayers annual values (when presented in undiscounted), especially in later years.

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[13] The Sayers report says*: No consideration is given to inflation or a shift in household and business inventories that may be flooded. This implicitly assumes income patterns remain as today. This could be considered for future inclusion if there is a spatial or demographic dimension to these changes.*

Table 58 Expected annual damage (EAD) for residential properties (direct) from coastal flooding under different climate scenarios (£ and % increase relative to present day, average population growth, WITH economic growth, current level of adaptation) (Source: Sayers et al. 2020)

EAD			**2050**	**2080**	**2080**	
£Million		**Present day**	**2°C**	**4°C**	**2°C**	**4°C**
UK	Coastal	82.0	254.5	340.9	663.9	1,019.8
			210%	316%	709%	1143%
England	Coastal	59.5	210.5	290.9	572.7	903.2
			254%	389%	863%	1419%
N. Ireland	Coastal	0.2	0.5	0.9	1.3	2.4
			211%	459%	762%	1413%
Scotland	Coastal	6.4	13.4	14.7	25.6	28.8
			110%	130%	301%	351%
Wales	Coastal	16.0	30.1	34.4	64.3	85.4
			88%	115%	301%	433%

Table 59 Expected annual damage (EAD, £million) for residential properties (direct) from fluvial and surface water flooding under different climate scenarios (£ and % increase relative to present day, average population growth, WITH economic growth, current level of adaptation) (Source: Sayers et al. 2020).

EAD			**2050**		**2080**	
£Million		**Present day**	**2°C**	**4°C**	**2°C**	**4°C**
UK	Fluvial	255	582	712	1,091	1,558
			128%	179%	328%	511%
	Surface	139	386	472	824	1,115
			178%	240%	494%	704%
	Total	394	968	1,184	1,915	2,673
			146%	201%	387%	579%
England	Fluvial	172.0	421.8	515.4	797.3	1,150.0
			145%	200%	364%	569%
	Surface	59.8	170.7	218.2	374.9	547.4
			185%	265%	527%	815%
	Total	231.8	592.5	733.6	1,172.2	1,697.4
			156%	216%	406%	632%
N. Ireland	Fluvial	6.9	13.3	15.9	26.1	34.4
			92%	129%	276%	395%
	Surface	14.1	43.5	52.1	90.6	118.4
			207%	268%	540%	737%
	Total	21.1	56.8	68.0	116.7	152.7
			169%	222%	453%	624%
Scotland	Fluvial	44.3	81.8	109.4	149.7	228.3
			84%	147%	238%	415%
	Surface	17.8	56.4	68.8	118.3	153.8
			217%	287%	565%	764%
	Total	62.1	138.1	178.3	268.1	382.1
			122%	187%	331%	515%
Wales	Fluvial	31.6	65.0	71.3	117.9	145.6
			106%	126%	274%	361%
	Surface	46.9	115.3	132.9	240.4	295.2
			146%	183%	413%	530%
	Total	78.4	180.3	204.3	358.3	440.8
			130%	160%	357%	462%

Table 60 Expected annual damage (EAD) for residential properties (direct) from ALL flooding under different climate scenarios (£ and % increase relative to present day, average population growth, WITH economic growth) (Source: Sayers et al. 2020). Current Level of Adaptation.

		2050		2080	
EAD (£Million)	**Present day**	**2°C**	**4°C**	**2°C**	**4°C**
UK	475.5	1,222.2	1,525.0	2,579.2	3,692.8
England	291.3	803.0	1,024.6	1,744.9	2,600.6
Northern Ireland	21.2	57.3	68.9	118.0	155.1
Scotland	68.5	151.5	192.9	293.7	410.9
Wales	94.5	210.4	238.7	422.6	526.2

As well as direct damage, flooding can lead to fatalities and injuries. These were estimated in the CCRA1 but were found to be low e.g. £42 million/year (fatalities) and £41 million/year (injuries) by the 2050s, central projection (Hames et al., 2012[ccclxvii]).

There has been less analysis of climate related health impacts from flooding, though some UK analysis of increased mental illness post-disaster at the national level (Hunt, 2012) indicates economic costs that are lower than fatalities and injuries above. The Environment Agency (2020ccclxviii) recently estimated the mental health costs from flooding (per adult household, per flood depth band within a property). These refer to work-based losses (economic activity lost) due to suffering a mental health condition, which is then added to the cost of treatment to provide a total loss per adult. Estimates range from £1,878 – less than 30cm flooding, to £3,028 for 30cm to 100cm flooding, and £4,136 for more than 100cm flooding.

The overall results are presented below. As highlighted above, the Sayers results can be used, but as these exclude most socio-economic change, an additional value is included (in brackets) with this included.

Table 61 Valuation of H3. Risks to people, communities and buildings from flooding. Scores climate and population only (climate and socio-economic change)

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	High	High (Very High)	High (Very High)	High (Very High)	Very high (very high)	Very high (very high)
England	High	High (Very High)	High (Very High)	High (Very High)	High (Very High)	
N. Ireland	Medium	Medium (high)	Medium (high)	Medium (high)	Medium (high)	
Scotland*	Med / High	High (high)	Medium (high)	High (high)	High (high)	
Wales	Medium	High (high)	High (high)	High (high)	High (high)	
Confidence	Medium	Medium	Medium	Medium	Medium	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation
The three portfolios in the research report on future flood projections influence the future increase in risk to properties and associated EAD (Sayers et al., 2020). Continuing Current Levels of Adaptation is expected to offset future EAD in the 2080s (under a 4°C high population growth scenario) by around £7.4 billion (all damages, not just residential, direct and indirect). Under the same scenario, an Enhanced Whole System is estimated to offset £8.2 billion EAD but only £6.4 billion is offset by the Reduced Whole System, meaning that the net increase in risk is much greater at around £2.8 billion.

It is important to note that residual risk remains under all scenarios as it is not realistic to eliminate all flood risk. National strategies in place (or in train) aspire to many of the elements of the Enhanced Whole System, the degree to which these are effectively implemented will determine the level of flood risk reduction. Note that the analysis of adaptation with full socio-economic change included (including economic growth), as in the additional tables above, has not been assessed.

There is a very large literature on the costs and benefits of flood protection for adaptation, indeed, it is the most comprehensively covered area in the literature (OECD, 2015[ccclxix]). These studies tend to find high benefit to cost ratios, for both hard and soft protection measures, and for grey and green infrastructure. However, values are highly site- and context-specific.

In terms of property resilience and resistance measures, there have been several studies that have investigated the costs and benefits of these measures. These include EA (2015[ccclxx]), Royal Haskoning DHV (2012[ccclxxi]) and Wood Plc (2019[ccclxxii]). The latter is most recent report found that a number of flood resilience and resistance measures could be considered no-regret adaptation measures (i.e. a benefit to cost ratio of greater than one in cases where there is a greater than 1% chance of Annual Exceedance Probability (AEP)). In general, this literature reports that all measures are more expensive if retrofitted rather than installed in new builds. For resistance measures, the difference between costs of retrofitting vs. incorporating into new builds are more modest. However, the applicability of each of these measures depends on the type of flooding (recurrence and depth), as this alters the relative cost-effectiveness (and benefit to cost ratio).

Given the residual damage costs even with current flood management policy, this is clearly an area where there are benefits of future action, and in many cases these benefits will outweigh the costs.

H4: Risks to the viability of coastal communities from sea level rise

CCRA3 Technical Report

This risk is focused on coastal change (physical change to the shoreline caused by coastal erosion, coastal landslip, permanent inundation or coastal accretion) that is of such severity that the long-term sustainability and viability of coastal communities is threatened. Chapter 5 of the Technical Report identifies that parts of the South and East coasts of England and the West coast of Wales already face risks to their viability as a result of coastal change. These are exacerbated by UKCP18 projections, which suggest greater sea level rise than had been previously.

Valuation

As highlighted above, there are UK specific studies on the impacts of climate change (sea-level rise and storm surges) on coastal flooding, in CCRA1, CCRA2 and CCRA3. These are considered in the previous risk and not included again here. However, there are potentially large and additional impacts on particular coastal communities, which would include multiple impacts (and economic costs) that go beyond the damage to property, and in severe cases, could lead to irreversible impacts. The potential economic costs of these events are potentially large, especially under extreme sea-level rise scenarios, though they depend strongly on the adaptation response, and on policy, i.e. whether to protect at all cost, or to abandon because of the high economic costs of action.

The CCRA3 Technical report highlights that since 1996 around 50 permanent properties and 30 temporary properties have been lost as a result of coastal erosion. Looking to the future, there are areas of coastline where it is unlikely to be economically viable to protect to high levels of sea level rise. It identifies North Norfolk at particular risk, villages along the coast between Cromer and Great Yarmouth particularly. In Wales, it identifies the Gynned coast in West Wales with Porthmadog, Pwlheli and Fairbourne being of such significant risk that it could affect their current and future viability.

The example given in the CCRA3 Technical Report is Fairbourne which has 461 residential and business properties with a population of around 700. Much of the village is projected to be below normal high tide levels within the next 50 years, and the Shoreline Management Plan (SMP2) policies for the area for periods 2055 to 2105 indicate that there may be a need for part, if not all of the village, to relocate or disperse elsewhere (Managed Realignment or No Active Intervention). Such a loss goes beyond the flood damages in H3, not least because it involves the complete loss of property (and thus property value) as well as the costs of relocation.

To explore this, we have undertaken a case study. This focuses on the possible changes by mid-century (i.e. the next 30 years or so). This looks at a managed retreat and thus abandonment of properties. In order to cost this, we consider the following cost components: loss of property; residents' relocation, and human health. However, we note that a range of other impacts including increased travel costs, loss of amenity and recreational opportunities and loss of services may affect both the directly impacted households as well as other households in the town but these impacts are not possible to value.

We assume that the cost of property loss can be approximated by the current average value of property in Fairbourne. Whilst a depreciation of property asset values may have occurred as a result of the Shoreline Management Plan (SMP2) policies being recently published for the area for periods 2055 to 2105, average prices have risen in the last 12 months. The current average house price in Fairbourne is estimated to be £160,000, according to the online property valuation organisation.[14] The total undiscounted cost to all property is therefore £73.76 million. Using the HM Treasury supplementary guidance and discount rates for intergenerational wealth transfer (HMT, 2008[15]), which are lower than the main Green Book guidance, the discounted cost for the decrease in property value would be £26.28 million. We also assume that there are no flood events before the properties are abandoned, noting that if this is not the case, additional costs will occur.

Household relocation costs may include: solicitors' fees in respect of sale and purchase; search, survey and property enquiry fees; mortgage arrangement/redemption fees; estate agents' buying/selling fees or advertising costs; removal costs (sea freight only for moves into the UK) storage costs; stamp duty; valuation fees; conveyancing and land registry fees. The allowance for these costs currently provided by the UK Government before employers are taxed on the financial support they are allowed to give new employees is £8000[16]. In the absence of observed data we assume that each of the affected households will incur a cost of £8000. The total undiscounted cost of relocation is therefore £3.69 million. The discounted cost is £1.31 million.

The main CCRA3 report indicates that 86% of those homeowners of the properties projected to be at risk of tidal flooding are currently suffering from deterioration in their mental health. The method suggested for the valuation of mental health impacts - outlined in UK Government appraisal guidance (Defra, 2020[ccclxxiii]) - is presented in relation to effects that arise from experiencing flooding or erosion rather than in anticipation of the climate impact. Given that there is such anticipatory anxiety, however, we utilise the per household monetary values presented in the guidance. Specifically, we use the cost per individual assuming a low but persistent mental health impact, of £1,878 per two-year period. We assume the current permanent population of 700 is impacted for the thirty-year time-period considered. The total undiscounted cost to health is therefore £19.72 million. The discounted cost over the 30-year period is £7.03 million.

Overall, the aggregate undiscounted costs of this case study are £97.22 million and the discounted costs are £34.62 million. Annualised costs are £3.2 million and £1.15 million respectively.

It is highlighted that some recent analysis indicates very high numbers of people might face similar issues, in the absence of adaptation, under extreme SLR scenarios. Lincke et al (2020[ccclxxiv]) estimate that under extreme scenarios (RCP8.5) 0.04% of the population in the UK might be forced to migrate, which is equivalent to tens of thousands of people, though it also finds these numbers would

[14] https://www.zoopla.co.uk/house-prices/fairbourne/

[15] This has a lower discount rate, though for the first 30 years the difference is minor, as it is 3% rather than 3.5%.

[16] https://www.gov.uk/expenses-and-benefits-relocation/work-out-the-value

be reduced very dramatically with adaptation. In this model, these effects are valued through a simple multiplication based on per capita income (Tol, 2002[ccclxxv]).

Given the evidence, it is difficult to value this risk with confidence. Based on the study from Fairborne, the likely equivalent annual cost is likely to be modest in the 2050s, even assuming that a number of similar small areas are lost. Note however, that there will also be additional costs from the impacts on people's health and well-being, as well as the indirect economic effects of these losses. A medium valuation is therefore assigned. It is possible that with higher sea-level rise in the late century, that this could rise to a high annualised value. Importantly, indirect costs from losing coastal towns and infrastructure are not accounted here but are expected to be significant (see H1 and B2).

Table 62 H4: Risks to the viability of coastal communities from sea level rise.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	Medium	Medium	High	High	Very high
England	Low	Medium	Medium	High	High	
N. Ireland	Low	Low	Low	Low	Low	
Scotland	Low	Low	Low	Low	Low	
Wales	Low	Medium	Medium	Medium-high	Medium-high	
Confidence		Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

<u>Adaptation</u>
In general terms, the literature reports that coastal adaptation is an extremely cost-effective response, significantly reducing residual damage costs down to very low levels (Brown et al., 2011[ccclxxvi]; Hinkel et al., 2014[ccclxxvii]; Lincke et al. 2018[ccclxxviii];). However, in locations with very few properties, such measures often have benefit-cost ratios lower than one. This may contribute to decisions that a community's long term viability is unsustainable, when viewed from the perspective of economic efficiency. However, many more issues are involved in such cases, such as threat to life should existing or upgraded defences be breached, and there is a need for any economic analysis to consider the wider issues, and also consider different perspectives including social justice.

H5: Risks to building fabric

<u>CCRA3 Technical Report</u>
Chapter 5 of the Technical Report identifies a number of climate risks to building fabric including subsidence caused by drought and dry soil, damp or excessive moisture due to flooding, and intense or vertical rain; and structural damage due to high winds. It identifies that the impact of climate change on these hazards (weather conditions) is highly uncertain as they are not well described in climate scenarios, and the evidence of impacts and costs to households, is limited.

<u>Valuation</u>
There are a number of different impacts that have been considered in terms of valuation.

<u>Wind storms</u> are among the most damaging extreme events in the UK. Climate change has the potential to alter the frequency and intensity of these storms and thus affect the distribution of insured and insured losses. However, the projections of these changes are uncertain, including the change in frequency and intensity, but also whether the North Atlantic storm track could shift in the future, resulting in fewer mid-latitude storms.

Some studies have indicated a small increase in the number of windstorms affecting the UK with the frequency and intensity of the most extreme windstorms increasing during the winter months. ABI / Air Worldwide and MO (2017[ccclxxix]) projected the changes in frequency and intensity of windstorms, looking at the average annual loss (AAL), i.e. annual insured loss aggregated over an entire year, for the 1.0% exceedance probability (100-year) loss, and the 0.5% exceedance probability (200-year) loss.). The analysis also indicated a possible increase of up to a 30% increase in the 100-year return level loss and up to 40% in the 200-year return period loss, though the distribution of these changes is not equal across the country. The resulting economic losses are shown below.

The results indicated a change in the overall AAL of 11%, 23%, and 25% for the 1.5 °C, 3.0 °C, and 4.5 °C cases, respectively (corresponding to RCP 4.5 at 2050-59, RCP 8.5 at 2070-79 and RCP 8.5 at 2090-2099). Importantly, the scenarios also suggest a possible increase of up to 40% in the 200-year return period loss, and approximately up to a 30% increase in the 100-year return level loss.

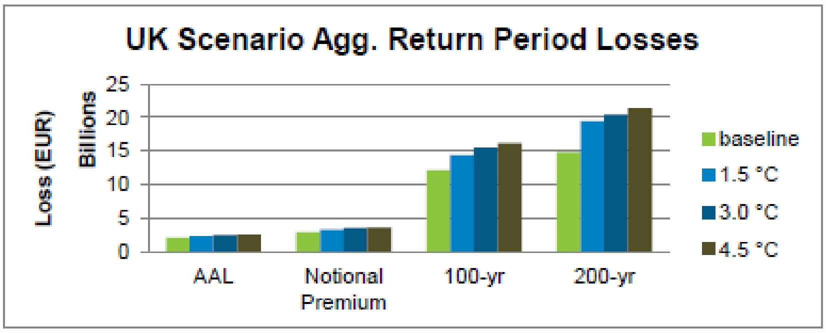

Figure 18 Average annual loss (insured), notional premium and 100 and 200 year losses for the UK. Source Air Worldwide and MO, 2017.

The report does include some disaggregation by region, which indicates potential differences in the relative increase. These indicate the largest increases occurring in the central UK, and potential decreases in the Southern UK. However, extreme care should be taken with these figures, because of the high uncertainty involved in the modelling.

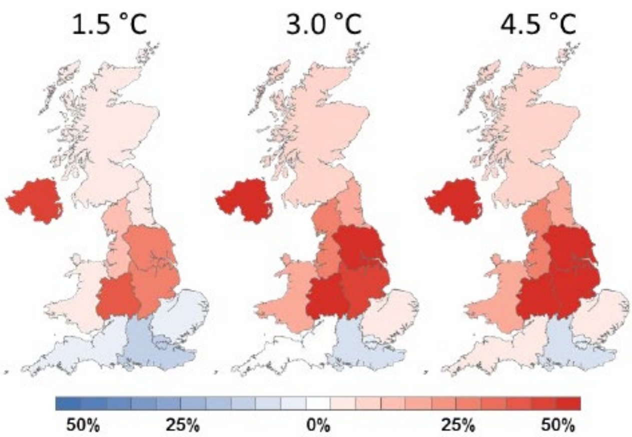

Figure 19 Percent changes in regional AAL relative to the stochastic baseline. Source Air Worldwide and MO, 2017.

There is also some analysis in the PESETA IV project on windstorm damages (Spinoni et al., 2020[ccclxxx]). This looks at windstorm damage (including all assets, including infrastructure). Based on the projections, which show modest changes in wind, it does not anticipate a large increase in costs, but does highlight that current costs are high when expressed as expected annual damage, and will increase even without climate change because of socio-economic change.

Table 63 Ensemble median Expected Annual Damage (EAD, expressed in 2015 €million) for the baseline (1981-2010) and warming levels for the alternative socioeconomic scenarios.

		Base economy			2050 Economy		2100 Economy		
Country	base	1.5°C	2.0°C	3.0°C	1.5°C	2.0°C	1.5°C	2.0°C	3.0°C
UK	528	550	552	473	899	900	1,639	1,640	1,403

Subsidence. Soil type (e.g. clay soils) and local vegetation are the dominant cause of subsidence. Clay soils with high shrink-swell potential underlie much of the densely populated areas of London and the South East of England. Other areas can also be susceptible to subsidence, for example the Vale of York and the Cheshire Plain. Older buildings and buildings with shallow foundations are at greatest risk.

Previous hot years have reported high subsidence claims (Hunt and Taylor, 2006[ccclxxxi]: Watkiss and Hunt, 2012 in CCRA1[ccclxxxii]). In the hot summer of 1990-91, the costs incurred as result of subsidence were reported at over £500 million. There was also a significant increase in claims in the very hot summer of 2003, which was estimated to have increased building subsidence claims by 20% in the UK, with 22,000 extra cases of subsidence, and estimated costs of £30 to £120 million. In 2009, there were 29,700 notified domestic subsidence claims, with a total value of £175m. During the UK summers of 2018 and 2019, there was also a rise in homes at risk to subsidence. The Association for British Insurers reported after the 2018 heatwave that over 10,000 UK households made claims totalling £64 million (ABI, 2018).

Previous studies have quantified and valued the potential costs of subsidence. Hunt (2006) estimated impacts of subsidence from climate change (on average) at £5 to 15 million/year in the 2020s, rising to £25 to 185 million in the 2050s and £115 to 315 million in the 2080s (note these are average impacts, the values in a particular year would be higher). Watkiss and Hunt (2012) estimated values for England only, considering impacts in other regions to be low. This was based on replacement costs as a lower bound estimate of the welfare costs associated with subsidence. This included residential buildings only (note that there are potentially additional costs for non-residential, but especially historic buildings). The values were for climate change only (no socio-economic change). The analysis found a very large range, with even potentially positive values in some cases (i.e. across the full projections). They report values of 20 million in the 2020s, rising to £50 million in the 2050s and £60 million in the 2080s, for a central scenario. These rise under a warmer drier future.

Table 64 Marginal change in domestic subsidence incidents per annum. Change due to projected climate change in the 2020s, 2050s and 2080s, compared to 1961-1990 climate (2008 households, no socio-economic change). (£m per year, 2010 prices, no uplift).

	£Million/year		
	2020s	2050s	2080s
England – central scenario	20	50	61
England – P10, low scenario	68	98	104

Moisture and damp. There is much less information on the potential impacts of climate change on moisture and damp, and thus no valuation estimates are possible.

Results. The impacts of storms and subsidence are brought together in the table below. The impacts of subsidence are considered medium for England, potentially rising to high in the 2080s 4°C. The impacts of windstorms are much higher, and considered high for the UK (and for England) currently and rising to potentially very high in the 2080s, though there is considerable uncertainty around future windstorms.

Table 65 Valuation of H5: Risks to building fabric.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	High	High	High	High	High - Very High	
Confidence	Medium	Low	Low	Low	Low	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation
Subsidence tends to be a slowly progressing threat, and most adaptation is reactive, in the form of repair once major problems emerge. There is well established information on the costs of reactive adaptation from subsidence insurance claims (see above), and indeed insurance is an adaptation response to current and future risks. There are potential benefits from more proactive approaches, with most of the literature focusing on monitoring, measurement and prediction (e.g. Erkens and Stouthamer (2020)[ccclxxxiii]), and these are a low-regret option in national adaptation planning and awareness raising to households. There is a wider literature on the costs and benefits of direct intervention measures to reduce subsidence, but most of this is focused on human induced subsidence (e.g. water related). For the shrink swell subsidence of most relevance to the UK, the main options are centred on proactive approaches already in use, e.g. vegetation control (trees) and local water management. For high risk areas, these are likely to be low regret.

An important response to windstorm risks is household insurance, which acts as a risk spreading mechanism for extreme wind events. The evidence from tropical wind storms indicates that retrofitting (for increased storm intensity or frequency from climate change) has high adaptation costs, especially for roofing upgrades (RMS, 2009[ccclxxxiv]), although it can lead to high benefits. There is less evidence for Europe, but this tends to report similar findings (Hunt and Anneboina, 2011[ccclxxxv]; UBA, 2012[ccclxxxvi]). These sources indicate reasonable benefit:cost ratios (at least for some options) (BEIS, 2019b; Spinoni et al., 2020[ccclxxxvii]). For household options, costs are lower in new builds, and can include siting and orientation, design and materials. The potential for increased building codes to cope with more intense windstorms is considered a low-regret option, however a review (ECONADAPT, 2017[ccclxxxviii]) has identified that benefit to cost ratios vary significantly with the risk level, the marginal costs of higher resilience, the existing cost and life-time of the asset, the costs of retrofitting based on local costs of materials and labour, and on the discount rate.

For damp or excessive moisture due to flooding, and intense or driving rain, the main current approach for managing risks for new buildings is through building standards and there has been recent research for moisture in buildings (MHCLG, 2019[ccclxxxix]). As highlighted above, there are potential benefits of a more integrated approach on moisture in buildings as part of a whole-house approach and accounting for the changing climate and potentially greater risks over time, although there would need to be an analysis of the potential costs and benefits of the climate uplifts, taking into account the long life-times and potential lock-in for new builds, but also the cost premium and nature of benefits (future, uncertain) (May and Sanders, 2017[cccxc]). The benefits of further adaptation for the existing building stock is highly variable and less well characterised, and there appears to be less economic evidence on potential options: this is identified as a potential gap.

H6: Risks and opportunities from summer and winter household energy demand

CCRA3 Technical Report
Chapter 5 of the Technical Report sets out that temperature is a driver of household energy demand. Heating demand dominates energy use in buildings at present. Climate change will reduce future heating demand, and the magnitude of this opportunity (benefit) is high, across all future periods and

scenarios, for all DAs. The future levels are uncertain, and depend on socio-economic change and also the potential rebound effect. Cooling demand is likely to increase with climate change but depends upon the uptake of mechanical cooling methods (air conditioning). The magnitude of this risk (cost) could be high after mid-century under high rates of warming in England. Net Zero policies will have big interactions with these risks/opportunities and also present additional costs to households to increase energy efficiency. This risk needs to be considered alongside overheating risks for households (discomfort and health, Risk H1),

Valuation

The valuation of changes in energy demand are some of the largest economic effects from climate change. These have been considered separately below.

Heating demand

Energy demand for residential buildings equated to [473TWh] in 2019 and around 65% of total domestic energy consumption is for space heating (BEIS, 2020[cccxci]). It is a significant component of household expenditure, and thus any changes to this from warmer temperaures will have a very large economic benefit, especially because these benefits will be experienced for all houesholds in all DAs.

This relationship is often captured through heating degree days[17] (HDD). HDD in the UK have been falling in recent decades (Kendon et al., 2019[cccxcii]). The decade 2010–2019 had 10% fewer HDD per year on average compared to 1961–1990. Future climate change will further reduce HDD, with recent estimates available from Hanlon et al. (submitted[cccxciii]).

Table 66 Change in HDD Ensemble median. Source Hanlon et al. (submitted),

	HDD 1981-2000 average	**HDD (degree days) Warming level change compared to 1981−2000 mean**				
		1.5°C	**2°C**	**2.5°C**	**3°C**	**4°C**
England	2342	−347	−517	−630	−737	−969
Northern Ireland	2495	−301	−467	−561	−683	−902
Scotland	2994	−334	−528	−642	−766	−1011
Wales	2447	−340	−505	−626	−738	−972

While space heating is negatively correlated with average temperature – and HDD - there are many other factors involved, not least building design and insulation, heating technology, energy prices, incomes, etc.

In the UK, national estimates of the energy and economic benefits of reduced winter heating were undertaken in CCRA1 (Capon and Oakley, 2012) using UKCP09. This reported a reduction in the projected levels of energy demand to heat homes across all regions in future decades. Annual space heating demand per household was projected to fall significantly, across all four countries. This reduction in demand was projected to be of the order of 15% by the 2020s, rising to 25% by the 2050s and 40% by the 2080s for the p50 Medium emissions scenario, compared to 1961-1990 baseline climate.

The economic benefits of these changes were very large, valued by Watkiss and Hunt (2012) as part of CCRA1. The marginal benefits from climate change alone, relative to the baseline period was estimated at an annual benefit of £0.4 billion to £1.5 billion/year for the 2020s, £0.6 billion to £2.5 billion/year for the 2050s and £1 billion to £3.4 billion/year for the 2080s. This used the long-run variable cost (LRVC) of energy supply and not the retail cost.

These estimates have been updated here. Again, we use the HMT Supplementary guidance on valuing energy use and GHG emissions (BEIS, 2019[cccxciv]). This sets out that for appraisal, changes in

[17] A degree day is an integration of temperature over time and is commonly used to relate temperature to particular impacts. The threshold values used in the UK are less than 15.5°C (heating) and more than 22° (cooling).

energy consumption impact the use of resources in the production, transportation, and final supply and use of energy, and that to value these impacts, analysts should use the long-run variable cost (LRVC) of energy supply[18]. For the calculation below, we use the long-run variable cost for gas as the heating fuel. In order to capture the uncertainties that the use of LRVC introduces a sensitivity has also been undertaken using the retail price, which leads to significantly higher values.

The economic benefits are very significant, i.e. £billions per year, and increase over time, under warmer scenarios. Furthermore, there would be similar reductions in winter energy demand for other sectors, i.e. in non-residential buildings, thus the benefits would be much larger than shown. When non-residential space heating demand benefits are included, the numbers below might double.

Table 67. Reduced winter heating (marginal economic benefit, £Million/year) due to climate change only (no socio-economic change), assuming current household stock, and gas heating. 2018 prices.

Long-run variable cost (LRVC)

	£Million/year								
	2020s			2050s			2080s		
	Med p10	Med p50	Med p90	Low p50	Med p50	High p50	Low p50	Med p50	High p50
UK	577.6	1246.4	1903.6	934.4	1112.5	1547.9	1491.0	1855.5	2381.5
England	452.9	960.2	1464.7	728.2	853.4	1213.7	1180.3	1448.6	1844.9
N.Ireland	56.3	106.3	156.3	94.5	106.0	129.1	140.6	163.7	209.9
Scotland	33.3	94.9	157.6	59.2	77.6	106.5	71.4	121.4	158.8
Wales	35.0	85.0	125.0	52.5	75.6	98.7	98.7	121.7	167.9

Retail price

	£Million/year								
	2020s			2050s			2080s		
	Med p10	Med p50	Med p90	Low p50	Med p50	High p50	Low p50	Med p50	High p50
UK	1895.5	3388.9	4856.3	3672.8	4040.8	4940.1	4822.6	5575.5	6662.0
England	1472.5	2605.1	3731.7	2830.9	3089.4	3833.7	3764.7	4319.0	5137.5
N.Ireland	175.3	286.9	398.6	337.8	361.7	409.4	433.2	480.9	576.3
Scotland	129.8	267.3	407.2	281.5	319.4	379.1	306.7	410.0	487.2
Wales	117.9	229.5	318.9	222.6	270.3	318.0	318.0	365.6	461.0

There are a very large number of caveats with these numbers. The analysis does not take account of future changes in heating demand from increases in population and the housing stock, that would occur from rising incomes, but conversely the decreases that would arise from efficiency improvements or technological change in heating appliances, or improved energy efficiency of the housing stock. The analysis also does not take account of the effect of future price levels on demand, or non-marginal effects. The level of gas use reductions here would have wider macro-economic effects, not least through reducing gas imports.

The analysis also does not take into account rebound effects. A reduction in energy bills frees up funds which can be spent on energy or other goods and services. Any resulting increase in energy use is known as the "rebound effect". This may offset some of the benefits, i.e. as households increase comfort levels, or else use the expenditure savings for other energy intensive activities.

CCRA1 also valued the associated benefits from reduced greenhouse gas emissions (using carbon price values, also from the DECC guidance) and reduced air pollution emissions. These were found to

[18] The LRVC is used instead of the retail energy price, because energy prices include:
- fixed costs that will not change in the long run with a small sustained change in energy use,
- carbon costs, since these are valued separately, and
- taxes, margins, and other components which reflect transfers between groups in society.

be significant, i.e. potentially £billions/year, but were only considered for the 2020s, as the study assumed by the 2050s low carbon energy would be used.

However, these values assume the use of gas for heating and thus are not aligned to net zero pathways. It is very difficult to estimate currently how these benefits might change along a net zero pathway. There would still be benefits from reduced winter heating, but they will be different (potentially higher or lower depending on levels of insulation, fuel switching and the price per unit of heating delivered, etc.).

The net zero target means there is likely to be a much greater focus on energy efficiency to reduce energy use in homes, and that forms of zero carbon energy are used for heating, rather than gas. There are still no clear policy commitments in the UK on how to deliver net zero for the heating sector. The Climate Change Committee developed techno-economic scenarios of the Net Zero report published (CCC, 2019[cccxcv]). These scenarios illustrate ways in which extensive decarbonisation of the UK economy could occur by 2050 (to demonstrate that a Net Zero emissions target by 2050 is plausible). This was further updated in the 6th Carbon budget (CCC, 2020[cccxcvi]). This sets out that different pathways are possible, either with zero carbon electricity, e.g. powering heat pumps, or from switching from natural gas to hydrogen for heating. This is accompanied by energy efficiency measures. The CCC 2019 report outlines the following key messages.

- In residential buildings, the parts of the stock which are generally easier and/or less costly to decarbonise include new homes, homes off the gas grid, homes suitable for district heating, and homes on the gas grid with relatively low barriers.
- For non-residential buildings, a combination of energy efficiency, heat networks and heat pumps lead to near complete decarbonisation.
- The 'Further Ambition' scenario additionally deploys low-carbon heating and energy efficiency measures for homes which are considered more costly and/or difficult to decarbonise. This includes homes on the gas grid with space constraints, and homes with heritage value. This scenario also includes the conversion of residual gas demand to hydrogen.
- In non-residential buildings, the 'Further Ambition' scenario abates all residual CO_2 emissions. Gas used for peak heating demand in heat networks is decarbonised by shifting to hydrogen.
- The analysis confirmed that reaching net-zero emissions in buildings is achievable but that it remains costly, with a total annual cost compared to a theoretical counterfactual without any action on emissions estimated to be in the region of £15 billion in 2050 (UK).
- Delivering this will require a clear trajectory of standards. This includes delivering commitments announced under the Future Homes Standard, alongside ambitious standards for new non-residential buildings, delivering commitments on energy efficiency standards across the stock, and a long-term regulatory approach for delivering low-carbon heat.

In summary, the net zero target will have a major influence on these benefits of reduced winter heating costs, because it will affect energy technology and fuel choice, household energy efficiency (e.g. building standards) and thus potential demand, as well as energy prices. However, the exact influence is very complex and depends on how the net zero target is met.

Note that while energy efficiency measures would reduce baseline energy heating demand, and thus reduce the benefits above, they delivery of electric or hydrogen powered heating is more expensive than gas, per kWh, thus there would still be very large economic benefits from warmer temperatures, even if energy efficiency reduced demand. However, climate change could also make net zero targets slightly harder to achieve, because it involves more complex consideration of designing household energy systems for a changing climate. It is much easier to design a new net zero energy system for a static climate than one that is changing, especially because the measures taken to improve energy efficiency have a direct influence on household overheating potential, and because if there is an increase in cooling demand, then it changes the potential option choice (i.e. from heating only to duel heating and cooling). Further work in this area is strongly recommended. The summary values are presented below.

Table 68 Valuation of H6a energy demand. Reduced heating demand.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Very high	+Very high	+Very high	+Very high	+Very high	
England	Very high	+Very high	+Very high	+Very high	+Very high	
N. Ireland	Very high	+High	+High	+High	+High	
Scotland	Very high	+High	+High	+High	+High	
Wales	Very high	+High	+High	+High	+High	
Confidence	High	Medium	Medium	Medium	Medium	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Cooling demand

Because the UK is a temperate country, there are currently low levels of cooling and air conditioning in use today. As a result, the impacts of warmer temperatures on summer cooling have received less attention in the UK, not least because demand for cooling has been historically low. Higher temperatures are associated with indoor overheating and discomfort. These involve cases where a physical endpoint does not result (morbidity or mortality) but there are impacts on comfort levels. These are additional to the health outcomes in H1. As highlighted above, there will either be more discomfort from higher temperature in homes and buildings, or higher air conditioning use for cooling, though it is double counting to include both. The additional costs of air conditioning are used here as a proxy for the welfare impact of discomfort.

There has been an observed increase in cooling degree days (CDD), described in the previous section alongside HDD. The state of UK Climate 2019 report (Kendon et al., 2019) reports CDD over recent decades. The number of CDD are orders of magnitude lower than HDD, but CDD have increased over recent decades, though in absolute terms the increase is very small. The cooler climate of Scotland and Northern Ireland means that CDD are much lower. UCP18 projects increases in CDD, available from Hanlon et al. (submitted).

Table 69 Change in Cooling Degree Days Ensemble median. Source Hanlon et al. (submitted),

	1981-2010 Average	**CDD (degree days) Warming level change compared to 1981−2000 mean**				
Index		**1.5°C**	**2°C**	**2.5°C**	**3°C**	**4°C**
England	21	+23	+37	+48	+67	+114
Northern Ireland	3	+6	+9	+12	+19	+32
Scotland	4	+5	+8	+9	+14	+24
Wales	10	+16	+23	+29	+41	+73

Future estimates of cooling demand are complicated, as the relationship between climate and cooling demand is affected by baseline socioeconomic changes (population, housing density, housing stock, insulation levels, technology, equipment penetration level, efficiency of cooling units, behaviour, perceived comfort levels, energy prices, income, etc.) and by mitigation policy, especially Net Zero. Income significantly affects penetration rates (De Cian and Sue Wing, 2019).

There is strong evidence that a warmer climate will be associated with higher air conditioning demand, based on econometric analysis in other warmer countries in Europe, although the level of the increase is projected to be modest for the UK for 2°C of warming (Damm et al., 2017[cccxcvii]).

National Grid have estimated uptake of air conditioners in the domestic sector could reach 18 million units by 2050. They estimate that this would add 19 – 39GW of peak electricity demand on a typical August weekend compared to electricity demand today (National Grid, 2018[cccxcviii]). Importantly, the changes in cooling demand with climate change have a strong geographical pattern across the UK, with a concentration in England and especially the South East. The study by Day et al., 2009[cccxcix]) for London projected cooling energy demand could rise from approximately 1.6TWh in 2004 to 2.2 to 2.5TWh by 2030 in the city (for a low and high climate scenario). A study by Sansom (2017[cd]) using the DECC 2050 Pathways, with UKCP09, reported that increased summer temperatures could result in a significant rise in cooling degree days (CDDs) by 2050 and necessitate some form of cooling for buildings, with potentially 5.1M to 12.8M households with cooling by 2050 with an associated demand ranging from 5TWh to 13TWh by 2050 under extreme hot weather. Future levels will depend significantly on the scenario and model uncertainty range, i.e. the risk of cooling demand grows under a 4ºC pathway towards the end of century.

CCRA1 (Watkiss and Hunt, 2012) looked at the potential increase in cooling. This was only able to provide indicative values, but these suggested that the monetised values for cooling could be in the range £10 – 99 million/year in 2020s, £100 – 1000 million in the 2050s, and in excess of £1000 million in the 2080s.

For this analysis, we use a range from 5 to 13 TWh, based on the reviews above for 2050, and combine this with the BEIS long-run variable cost for electricity. This would indicate a value of £537 million/year to as much as £1.40 billion/year, respectively. There are no data for the 2080s, but the rises could be very significant under a 4°C world. There are a very high number of aspects here. The increase in future years is uncertain and will depend on many other factors. There is also a question of whether future cooling demand is met mechanically – noting there are passive and other alternatives (see the CCRA3 Technical Report, Chapter 5). An indicative valuation is provided below. The risk is considered lower in the devolved administraions compared to England, however, there is not good data, and further, there could be higher magnitudes under low likelihood high impact scenarios (i.e. warmer scenarios).

It is highlighted that there will also be increased cooling demand in non-residential buildings and by business and industry. These cooling costs are likely to be more significant than for homes, because of occupational standards (for building comfort).

Table 70 Valuation of H6b energy demand. Increased cooling demand. Note includes residential and non-residential space cooling.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	High	High	High	High	Very high	
England	High	High	High	High	Very high	
N. Ireland	Low	Low	Low	Low	Unknown	
Scotland	Low	Low	Low	Low	Unknown	
Wales	Low	Low	Low	Medium	Unknown	
Confidence	High	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

For heating, a more considered analysis of this opportunity could allow potential benefits to be maximised, but there is no information on what the costs and benefits of such action could be. What is clear is that there is a need for better integration of mitigation-adaptation linkages in Net Zero policy analysis, and subsequent government intervention to deliver Net Zero. There is a strong economic case for such action based on the value of information, as this could significantly reduce the costs of delivering net zero for the household sector (or to put another way, in a case where this information is not included, incentives will be introduced to deliver higher heating demand than is needed).

For cooling, mechanical cooling has costs and benefits that can be compared to alternatives. These include a wide range of options associated with buildings (passive ventilation), behaviour, green infrastructure and land-use planning. These were set out in Risk H1. There is some information on the economics of AC versus alternatives, with analysis of the costs and benefits of many options (see H1). These studies generally favour passive cooling, but there are differences between existing building and new builds, and the timing of installation and when overheating risks occur in the future is also important (reflecting the different cost profile of capital and operating costs). At the current time, the higher externalities of air conditioning (carbon and air pollution) tend to reduce the attractiveness of this option, but this will change with decarbonisation of the electricity system under Net Zero. In a case where air conditioning is not discouraged (i.e. if choice of cooling is left to households and the private sector, and therefore met with mechanical cooling, passive or other alternatives, or cooling demand is unmet), then it would be expected that penetration rates for AC would rise significantly in England (as indicated in the evidence above). In this case, there would still be benefits from further action, notable with energy efficiency standards for cooling equipment (low or no-regret), as well as energy efficiency awareness programmes (as there is currently for heating). Such programmes already exist for commercial buildings, but have not yet been transferred to residential ones. In a case where passive cooing is favoured, there are a range of further actions needed, which are set out in H1.

H7: Risks to health and wellbeing from changes in air quality

CCRA3 Technical Report

Chapter 5 of the Technical Report presents the evidence of linkages between air quality and climate change. While climate change could increase ozone levels, including during heat-waves, air pollution emissions from energy related combustion are falling rapidly, and are expected to decline significantly under Net Zero scenarios, thus the baseline level of pollution and interactions with climate change will reduce the future risk for outdoor air quality. It also highlights that pollen risks are likely to change with climate change, but the implications for health are not clear. There is very little evidence for the impact of climate change on indoor air quality, though the chapter highlights that household energy measures have the potential to worsen indoor air quality unless measures are taken to avoid this.

Valuation

There is an established literature on the valuation of air pollution in the UK (Defra, 2020[cdi]), especially the impact on health, and this has been applied in national air quality strategies. This uses a similar approach to H1, considering the resource costs, opportunity costs, in terms of lost productivity, and dis-utility. These same approaches can be used to value changes in air pollution from climate change.

There have been several studies on the impacts of climate change on air pollution. CCRA1 quantified the effects on ozone in terms of additional mortality (Hames and Vardoulakis [cdii]) and these were quantified using valuation endpoints from Defra guidance, based on a VOLY approach. The estimated impacts were low. The IMPACT2C project also looked at the effects of climate change on air quality (Lacressonnière et al., 2015[cdiii]), and undertook quantification and valuation. This found future impacts were low (in terms of additional fatalities) for ozone. These were valued, using a VPF and VOLY approach (as H1), with estimated impacts of the UK (average of four models for 2°C of warming globally) of £0.9 million (VOLY) to £27.7 million/year (VPF) (updated to current prices), though there was a considerable range around these. The same study also looked at the potential change in particulate matter in the UK. This generally found models projecting a reduction in particulates, which when valued (in terms of long-term life years saved), indicated benefits in excess of £several hundred million/year for the 2°C scenario.

For this endpoint, the present-day risks are attributable to other factors (climate is a minor component) and thus only future incremental values are shown.

Table 71 Valuation of H7a: Risks to health and wellbeing from changes in air quality.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK		Low	Low	Low	Low	
England		Low	Low	Low	Low	
N. Ireland		Low	Low	Low	Low	
Scotland		Low	Low	Low	Low	
Wales		Low	Low	Low	Low	
Confidence		Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

There is a further risk of changes in aeroallergens, such as pollen concentration, volume and distribution, but quantified estimates are lacking. However, the costs of aeroallergens are currently very high in the UK (e.g. Allergy UK has estimated an estimated £7 billion in lost productivity each year from hay-fever alone, and there would be potential additional effects on asthmatics, as well as additional costs from medical cost and dis-utility) and thus any increase in these would lead to high economic costs. Further, baseline levels are not declining (as with air pollution) and thus these are potentially more important for the future.

A separate table is presented for aeroallergens. While the evidence is not available, if an effect does exist, it is possible it could be high or very high.

Table 72 Valuation of H7b: Risks to health and wellbeing from changes in aeroallergens.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK		Unknown	Unknown	Unknown	Unknown	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

There has been detailed analysis of the costs and benefits of options for reducing outdoor air pollution, which have supported the development of national air quality standards and policies from the European Commission's Clean Air For Europe package and policies (EC, 2013[cdiv]) and the UK Clean Air Strategy (Defra, 2019[cdv]) with well-established methods for valuation (Defra, 2020a). It is also highlighted that these existing air quality policies will significantly reduce air pollution levels, including background levels of regional pollution from Europe (which are important for particulate and ozone levels in the UK), as well as direct emissions from sources in the UK. This means future air pollution levels should be much lower than current, and the marginal effect of climate change will act on a much lower baseline (Lacressonnière et al., 2015: 2017[cdvi]). The future levels of air pollution will fall even further with the implementation of Net Zero policies.

There may be benefits of additional adaptation (to target climate-induced changes in air quality and with regards to Net Zero drivers) which could address the most climate-sensitive pollutants. Climate change could be more explicitly considered within existing air quality policies and identified air quality improvement measures). Potential areas where further action might be beneficial are improved early warning and response plans for extreme events, notably where there is an interaction between heat and air quality, and work on the costs and benefits of adaptation to improve indoor air quality.

H8: Risks to health from vector-borne disease

CCRA3 Technical Report
Diseases transmitted by arthropod vectors (insects and ticks) are sensitive to temperature. Chapter 5 of the Technical Report outlines that risks of mosquito-transmitted diseases are likely to increase in the UK, but that the risk that malaria may become established remains low. It also highlighted that Culex-transmitted diseases will increase in the UK and the Lyme disease cases may increase with climate change due to an extended transmission season and increases in person-tick contact.

This risk is also covered in chapter 7, ID9: Risk to UK public health from climate change overseas, and there is some potential overlap.

Valuation
Climate change will also change the prevalence and occurrence of some vector-borne diseases (VBDs). The valuation of the impacts on public health of these diseases is possible, if there are quantified estimates of the risks. The welfare costs are based on the medical treatment costs, the costs of lost productivity in paid or voluntary work, and the pain and suffering associated with these illnesses.

At the present time, reported vector borne cases are acquired as a result of travelling to endemic areas overseas. The number of cases is low (there are a few hundred cases of dengue fever each year, and lower numbers of chikungunya, usually under a hundred, though there are year to year variations, PHE, 2013[cdvii]). The potential increase in these cases is projected to rise with climate change, but the economic valuation is likely to be low provided that cases only arise from travel, i.e. if these do not become endemic (See Chapter 7). The Technical Report considers that the current system of control and treatment of mosquito borne disease is sufficient to contain identified outbreaks. As long as this system is maintained future outbreaks under climate change are likely to be minimal, and the overall risk remains low. The magnitude scores in the table below reflect this judgement. However, if any diseases became endemic, this would lead to very different scores.

Lyme disease is present throughout the UK. Lyme disease is the most common vector-borne human infection in the UK. There are approximately 500 to 1500 cases reported each year in England and Wales, and a further 100 – 200 in Scotland, but it is estimated that there are between 1,000 and 2,000 additional cases of Lyme disease that are not laboratory diagnosed (PHE, 2018[cdviii]). While the disease can be treated with antibiotics, it has high welfare costs if untreated, from the combination of lost time and dis-utility. The Technical Report does not provide estimates of the potential effects of climate change on the number of cases of Lyme disease.

In much of Europe, Tick-borne encephalitis (TBE) is endemic. The potential spread of tick-borne disease in the UK could be important, as prevalence is changing due to climate change. In Sweden, Slunge et al. (2019) [cdix] found that the mean WTP per trip to avoid areas with different levels of tick-borne disease risk ranged from £10 to 70. This study also reported a market price of approximately £100 for a vaccine (which provides an alternative value, based on prevention costs as proxy) though Scasny et al. (2020)[cdx] report a lower value of £20 to get a vaccination in three Central European countries. This indicates that costs in other European countries where TBE is endemic are high (at tens of millions per year). This suggests that total costs in the UK might be similar if the disease became widespread, e.g. which might plausibly in later years, although there is currently no evidence on the likelihood of this happening.

Table 73 Valuation of H8: Risks to health from vector-borne disease

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low to medium	Low to medium	Low to medium	Medium	Medium	Medium
Confidence	Medium	Low	Low	Low	Low	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

The main benefits of further action are in enhanced monitoring and surveillance systems, including early warning, and these can be considered a low-regret option (WHO, 2013[cdxi]). There are some estimates of impacts and studies of the WTP for vaccination against tick-borne encephalitis (Slunge, 2015[cdxii]), the cost-effectiveness for lyme disease (Hsai et al., 2002[cdxiii]) and a cost-benefit analysis of TBE (Desjeux et al., 2005[cdxiv]). These studies report that tick vaccination programmes have high costs, and in the CBA study, the benefit to cost ratio was below one, though the overall ratio depends on the baseline risk levels.

H9: Risks to food safety and food security

CCRA3 Technical Report

Chapter 5 of the Technical Report identifies that climate change is likely to be important risk for food safety in the UK through a range of pathways. Increases in extreme weather patterns, variations in rainfall and changing annual temperatures will impact the occurrence and persistence of bacteria, viruses, parasites, harmful algae, fungi and their vectors. Climate change may affect food security in the UK through variability in access to food due to disruptions to the supply chain from arising weather events and climate hazards.

Valuation

There have been a number of studies on climate and food-borne disease, notably salmonellosis. Kovats et al (2011[cdxv]) valued the relevant cost components of the disease, i.e. treatment costs, opportunity costs and dis-utility costs, with a central value of €5,250. The estimated welfare costs in the UK were €2.6 million/year, €5.3 million/year and €7.7 million/year in the 2020s, 2050s and 2080s respectively, for an A1B scenario. Under an E1 (mitigation) scenario, these fell to €5.2 million/year in the 2080s. The analysis also undertook a sensitivity with a declining rate, reflecting improving food standards, which halved future incidence rates (and costs) under climate change.

A latter study (IMPACT2C, 2015[cdxvi]) estimated the resource costs of additional hospital admissions and additional cases of salmonellosis and campylobacteriosis at around €700 million in 2041-2170 period for the A1B scenario for all of Europe. This would imply higher estimates (than the Kovats study above) for the UK.

The impacts of food security are considered in Chapter 3 (natural environment) and in Chapter 7 (International). The economics literature does not anticipate effects on food security for the UK, although there is the potential for price increases, especially for higher warming scenarios. Risk ID1: International Risks to UK food availability, safety, and quality (no adaptation) is rated as a potentially very high risk, but with a very large range (in that potentially large benefits could also arise). The issues of international food security are not included additionally here.

Table 74 Valuation of H9: Risks to food safety and food security.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	Low - medium	Low - medium	Low - medium	Low - medium	
Confidence		Low -	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

<u>*Adaptation*</u>
The economic impacts of food-borne disease and food safety are well understood. The FSA has developed a cost of illness model, monetising direct and indirect costs associated with food-borne illness (including food-borne Norovirus, Salmonella and Campylobacter). Measures to improve food safety, food regulations and education on food handling and safety, coupled with horizon scanning and continuous monitoring for emerging risks, are likely to be a low regret option (WHO, 2013[cdxvii]). There are some economic studies that have assessed the economic benefits of maintaining or reducing food related disease cases in the UK under future climate change (e.g. Kovats et al. (2011[cdxviii])), and these find the economic benefits could be significant if the current levels of infection are maintained or increased.

For food security, there are existing actions being taken to build the resilience of food supply chains, though these have a focus on the private sector. However, the complexity of supply chains and their multi-staged processes, coupled with the uncertainty around climate change impacts, indicates that the private sector might struggle to take all appropriate actions, and there is a role for Government to play in removing some of the barriers to enable and encourage private sector adaptation, as well as ensuring a higher level of resilience along supply chains. There has been some analysis of adaptation options in this area (Watkiss et al., 2019[cdxix]) which has identified early low and no-regret options, but also highlighted the need for adaptive management, research and learning.

H10: Risks to water quality and household water supplies

<u>*CCRA3 Technical Report*</u>
Chapter 5 of the Technical Report identifies that parts of South East England are already water stressed and that climate change could lead to water supply-demand deficits by the middle of century in England and parts of Wales. Climate change may also increase the risk of contamination of drinking water through increased runoff and flooding events, and there could be increased risks to health from contact with bathing water (sea, lakes and rivers) and harmful algal blooms with climate change. Private water supplies are particularly important in Scotland and Wales and are likely to be affected by climate change.

<u>*Valuation*</u>
The key metric of relevance for the physical impacts of climate change is the water supply-demand deficit. In turn, this affects the key economic metric, the welfare value of water (and the welfare costs of water supply disruptions).

Water companies have a statutory duty to provide household and non-household customers with a reliable supply of water for domestic and business purposes. They must also ensure future demand will be met by sufficient supply capacity. Household water supply interruptions occur when water companies are unable to meet demand and therefore impose restrictions on customers' usage.

In the UK, the most significant recent drought occurred in 1976 when the public water supply was interrupted and stand-pipes were in use in places. Following the changes made after this event, there has not been a case where standpipes have been required, but the CCRA2 report (Kovats and Osborn, 2016) and CCRA3 chapter (Brisley and Kovats, 2020) have identified a number of smaller, localised droughts events or near misses. Private water supplies owners are responsible to plan for interruptions, however local authorities may help to provide alternative supplies in times of drought.

The economic costs of water supply interruptions can be significant. Some events have led to costs for business, notably the 2012 drought in England, but these are captured in the next chapter.

There is some WTP data, but these are for incremental improvements. For example, a Wessex Water study (2018[cdxx]) found that WTP for the improvements in the risk of restrictions to access of essential water supply from 1 in 200 to 1 in 500 per year is £1.23/hh/year. However, this estimate does not capture different WTP to avoid different type of interruptions, e.g. with different duration and timing of the restrictions, as well as their risk and whether there is a warning. There are also similar studies from other water companies, and these would be useful for public policy, but many are not available (see also Chapter 4 discussion). Values depend on the type, duration and timing of the restrictions.

There have been studies on the impacts of climate change on the water supply-demand balance, though it stressed that other factors (notably abstraction rates and future demand from other factors) are critical as well in the overall balance. CCRA1 (HR Wallingford, 2011) undertook an initial analysis of the water supply-demand deficit, combining UKCP09 with population projections. To value this, the analysis used supply side cost data (the adaptation cost to address the deficit), as a proxy for the welfare cost. This was undertaken for two scenarios, one with current socio-economics and one with rising future population (and higher water demand). The results for the 50% probability level under the Medium emissions scenario were +£12m, -£141m and -£212m per annum for the 2020s, 2050s and 2080s time periods respectively (climate only), with higher impacts of -46m, -275m and -416m per annum with climate and socio-economic change.

Table 75 Annual water supply-demand balance in the UK –marginal climate change impacts and climate and socio-economic impacts (population) on Deployable Outputs. Source CCRA1. £million/year, 2010 prices, no uplift, no discounting; 150 l/h/d per capita consumption.

		Climate change only				Climate change and population change (baseline scenario)		
Climate change scenario		Low Emissions	Medium Emissions	High Emissions		Low Emissions	Medium Emissions	High Emissions
2020s	p10	108	114	109		50	56	50
	p50	11	12	10		-46	-46	-46
	p90	-97	-102	-97		-155	-161	-156
2050s	p10	36	6	-26		-94	-123	-156
	p50	-106	-141	-174		-239	-275	-310
	p90	-245	-282	-296		-382	-421	-437
2080s	p10	-11	-86	-124		-204	-282	-323
	p50	-166	-212	-229		-366	-416	-437
	p90	-296	-317	-338		-503	-530	-557

HR Wallingford (2015[cdxxi]) for the CCRA2 re-assessed the supply-demand balance in the UK with climate change. They estimated a total of 27 water resource zones (WRZs) would have a supply-demand deficit of greater than 5 Ml/d in their water company resource plans, and estimated a negative supply-demand balance for England (but a surplus in Scotland and Wales). This did not extend to an analysis of the economic costs.

However, these projections need to be seen in the context of water companies and the regulated environment. Water companies are required to produce a Water Resources Management Plan (WRMP). These have a 25-year planning period and are updated every five years. If a supply-demand deficit is projected, then these consider options to reduce deficits. Water companies are also required to produce Drought Plans. These demonstrate how each water company would manage the security of supplies (demand and supply options) in the event of impending or actual drought events (Water UK, 2016[cdxxii]). It is noted that climate change medium emissions p50 and population projections are already factored into the these.

HR Wallingford (2020[cdxxiii]) provided the most up to date analysis in the research work for CCRA3. This included the latest water company resource plans. This found that the UK as a whole is currently in surplus of around 950 Ml/d. However, around 16.7 million people live in water resource zones that are currently operating in a deficit (7.89 million of which are in London). They report that at the national level, household consumption accounts for more than half of the demand for public water supplies. The study used UKCP18 to look at the future supply-demand balance (Ml/d) by region, in the mid-century (central population and no additional adaptation action) based on water companies maintaining the baseline target levels of service and drought resilience as specified in their latest water resource plans. The study found that, overall, the UK faces a supply-demand balance deficit of between -650 and -920 Ml/d, which corresponds to the daily usage of around 4.7 – 6.6 million people (based on the present day average per capita consumption of 140 l/h/d). The vast majority of this impact is in England. Note that these values assume that water can be freely transferred between supply systems around the country as a whole to where required: even if this could be realised (at significant cost), this would also be associated with additional operational losses.

At mid-century, the difference in climate change impact between 2°C and 4°C worlds is around 270 Ml/d at a national scale, whereas the difference in impact between the low and high population projections in the mid-century is around 3,220 Ml/d day at a national scale. Whilst 270 Ml/d is small compared to the baseline nationwide demand, it is nearly 30% of the current supply-demand balance surplus. The vast majority of this impact is in England (220 Ml/d). By the late century, under central population projection growth and no additional adaptation action, the deficit across the UK was projected to be between around 1,220 and 2,900 Ml/d (2°C to 4°C range). The deficit is driven by England. In contrast, Wales, Northern Ireland and Scotland all maintained a surplus supply-demand balance. However, the combined surplus is not sufficient to counteract the deficits located primarily in England even if the infrastructure were available to transfer the water. range of impact between a 2°C and 4°C world is projected to increase compared to mid-century, with the difference of around 1680 Ml/d at a national scale.

It is stressed that there are extremely large ranges around these values from the uncertainty in the climate projections. The full range includes much more severe possible outcomes for England, although also potentially more modest impacts.

It is possible to derive indicative values for these changes, using a similar supply side cost analysis as in CCRA1, as a proxy for possible welfare costs. The analysis has used a central value of £0.05 million Ml/day annually (2010 prices). These values have been updated to current prices and applied to the new estimates from the HRW (2020) study (above in the graph, reported in the table below as min, medium and max estimates), to provide some indicative numbers. These indicate modest costs for England. However, it is stressed that this approach has high uncertainty (in terms of values presented) and should only be considered as a high-level indicative approach.

Table 76: Variation in supply-demand balance due to climate change in the late-century under a 4°C world, assuming a central projection population and current and announced adaptation scenario, and £/Ml/d (Source: HRW, 2020 and author's calculations) (2020 prices).

	Million l/d			**£/Million l/d**		
	Min	**Median**	**Max**	**Min**	**Median**	**Max**
England	-2640	-910	+600	-155.5	-53.6	35.3
Northern Ireland	+120	+150	+220	7.1	8.8	13.0
Scotland	+360	+490	+650	21.2	28.9	38.3
Wales	+120	+180	+250	7.1	10.6	14.7

In addition to the supply-demand balance, there are additional potential welfare costs from major drought events. Extreme events such as drought could potentially become more frequent in the future, with resulting implications on water availability. The current water resource planning framework does allow for this, and has typically focused on the worst historic drought experienced by the period of observed records (up to 200 years, and therefore broadly equivalent to droughts of return period of around 1 in 200 years).

There are potentially large welfare costs from such an event (>1 in 100 year event). The willingness to pay elicited from the available literature to avoid Level 4 restrictions[19] has been estimated between £40/hh/yr and £160/hh/yr per avoided day of Level 4 interruption (Water UK, 2016). However, most of the literature is focused on the potential additional costs to address these risks, but these do provide some indication of a proxy value for welfare.

A 2016 study carried out by Atkins et al. for Water UK (Water UK, 2016[cdxxiv]) examined supply/demand vulnerability to more extreme drought events than considered under the current regime under climate change, including a number of dry future scenarios. They report that under more severe/extreme drought scenarios, DO would be reduced significantly compared to the worst historic scenarios; with residual deficits, especially in some regions. A further study, Atkins (2018[cdxxv]), assessed the costs of implementing emergency measures as part of the UK National Infrastructure Commission (NIC) analysis. Based on Atkins 2018, NIC (2018[cdxxvi]) estimated that in England the total costs between 2020 and 2050 of implementing emergency measures to provide household water supply during a 0.5% drought (1 in 200 year event), weighted by the occurrence probability, ranged between £13 and £16 billion (2018 prices). The total costs over the same period of implementing emergency measures against a 0.2% drought were between £21 and £27 billion (costs on a present value basis (2018 prices) weighted by the occurrence probability.

Water UK (2016[cdxxvii]) estimated that a 'twin track' approach of demand management coupled with appropriate development of new resources and potential transfers is the most suitable strategy for providing drought resilience in the future. They estimated that total costs per annum (by 2040) for all potential future scenarios (under the BAU base demand management strategy) to maintain resilience at existing levels in England and Wales was between £50 million and £500 million per annum in demand management and new water resource options. If resilience to 'severe drought' was adopted, this increased to between £60 million and £600 million and for resilience to extreme drought, between £80 million and £800 million per annum. These estimates compare favourably to household WTP, and the analysis found high benefit to cost ratios for increasing drought resilience.

There are some further issues that add complexity, that have not been considered in the valuation. A study by Mansour and Hughes (2017[cdxxviii]) commissioned by the Environment Agency looked at future groundwater recharge projections for Great Britain (England, Scotland and Wales) under conditions of climate change. The authors found that for the historical simulation (1950-2009) the recharge season was between five to seven months each year (September to April), but appeared to reduce to three to four months for the future climate predictions. The authors found that the recharge season was projected not only to be shorter but also "squeezed" into fewer months, resulting in greater "lumpiness" of the recharge signal.

HRW (2020) also considered environmental flows, the approach to which has a large influence on the availability of water at average low flows at a catchment scale in both the mid- and late century. However, the authors observed that the choice of approach to environmental flows would impact future catchments. Under a fixed (rather than proportional) environmental flow scenario, reductions in flows at Q95 due to climate change would result in more severe water reductions, with catchments in west Wales, north west and south west England projected to not be able to meet their current environmental flow requirements by the mid-century, and showing negative available resource.

[19] Severity 4 restrictions - Emergency Drought Orders: these are the most severe type of restrictions on household water use and imply the use of standpipes and/or rota cuts (Water UK, 2016).

There are some other valuation studies which have considered future droughts. The PESETA study looked at the impacts of droughts in Europe (Cammalleri et al., 2020[cdxxix]), for current and future economic costs. It estimated current annual losses from drought to be around 9 €billion for the EU (including the UK), and that these estimates could increase five time under a 3°C scenario, with public water supply accounting for between 9-20% of the total damage. It identified Belgium, Greece, Ireland, Portugal and the UK as showing the strongest increase in losses relative to now, although specific UK Values are not presented.

<u>Water quality and water contamination risks</u>
Climate change can impact on water quality through various ways. In general, changes in rainfall patterns and more frequent extreme events (droughts, floods) are expected to alter the flow regimes and temperature of rivers and reservoirs, affect groundwater levels and recharging, and increase the temperature. All these factors could affect the quality of water for drinking, farming, and recreational purposes (though recreation is considered in Chapter 3).

The potential impacts on water quality and/or from water contamination, could lead to potential health impacts, which can in theory be valued using similar analysis as for other health endpoints, from increased incidence of waterborne diseases such as diarrhoea and gastroenteritis. There seems to a general consensus in the literature around the higher risk of water contamination after flooding and its health implications. However, the magnitude of such risk is unclear. There is not a detailed impact literature on the likely increase in these diseases under future climate change, which makes valuation challenging. These impacts may also lead to high treatment costs, i.e. restoration measures or the increased cost of treating water for potable supply. It is likely that these risks could be higher for private water supplies. Approximately 525,000 people in England, 80,000 in Wales, and 150,000 in Scotland live or work in premises with a private water supply (the number for Northern Ireland is not known) (Kovats and Osborn, 2016).

An early analysis by the Environment Agency (2008[cdxxx]) assessed the potential impacts of climate change on water quality in five river systems in the UK: the Lambourn, the Tamar, the Lugg, the Tweed and the Tame. These rivers represent differing geology and geographical locations around the UK and differ significantly in the extent to which they are impacted by agriculture or point sources of pollution (Environment Agency, 2008). By running the models for four UK Climate Impacts Programme (UKCIP) climate change scenarios for three periods (2010s, 2020s and 2050s) the study concluded that overall, the changes predicted by the modelling project were not large, suggesting there was no immediate need to change the processes of water quality planning (Environment Agency, 2008). However, the authors stressed that different results were obtained by using different simulation models, and warranted for further research to be undertaken.

There can also be health impacts if there are water restrictions during droughts. These can arise from the local transport of water (rather than from tankers or standpipes). For every 2000 customers affected by a boil water notice there is anecdotal evidence (based on interviews) that one customer would fall ill and require hospital admission (Atkins 2018 for NIC).

Phillips et a. (2018[cdxxxi]) investigated both the economic and well-being benefits of bathing waters by collecting both quantitative and qualitative data (through various methods incl. surveys) across five bathing sites in Scotland in 2017. They found that local economies benefit from visits to the beach, generating nearly £9m in gross value added (GVA) across the five locations. Bathing water quality was found to be an important aspect explaining the perceived restorative and well-being effect of sea waters. In fact, the worsening of bathing water quality was found to impact on the number of visits to sites, leading to a reduction in the number of visits by 5%-35 and economic losses worth £0.2-3.19 million per annum. This study also estimated WTP to improve bathing water quality from poor to sufficient, good and excellent at £39, £46 and £85/hh/year respectively (table below). The value of reducing by 1% the number of beaches failing quality standards has been estimated at £2m per annum (annualized) for the whole of Scotland.

Similarly, in Wales, the tourism industry along the coastline contributes over £700 million each year to the Welsh economy, and a worsening of bathing waters could impact the local as well as the national economy.

Nevertheless, there is uncertainty around how climate change will affect water quality, making a quantification and evaluation of risks complex. The CCRA3 chapter identifies an association between weather factors, bathing water quality and infectious intestinal disease, but again, there is a lack of information on quantification to allow valuation. There are estimates for welfare benefits of bathing water, and the costs of maintaining bathing water, but there is insufficient evidence of how climate change will alter bathing water quality to allow valuation.

<u>Summary</u>
The valuation estimates are brought together below. The evidence shows that the supply/demand deficit is mainly driven by England. A separate table is presented for water quality, although there is insufficient evidence to make a valuation estimate for this risk (though the Evidence Chapter assigns a medium score).

Table 77 Valuation of H10: Risks to household water supplies

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK						
England	Medium	High	High	High	High	
N. Ireland	Low	Low	Low	Low	Low	
Scotland	Low	Low	Low	Low	Low	
Wales	Low	Low	Low	Low	Low	
Confidence	Medium	Low-Medium	Low-Medium	Low-Medium	Low-Medium	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<1 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Table 78 Valuation of H10: Risks to water quality

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK		Unknown	Unknown	Unknown	Unknown	
Confidence						

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

<u>Adaptation</u>
There are studies which have considered the overall costs and benefits of national level action to reduce the risk of water scarcity. These include supply side measures, which are discussed in Chapter 4. They also include marginal abatement cost curves of emergency measures for droughts (Atkins, 2018[cdxxxii]), as well as the estimates of costs and benefits of measures to provide household water supply during droughts (National Infrastructure Commission, 2018[cdxxxiii]). Alongside this, there is a complementary set of demand-side measures that can be introduced by homes, many of which are no-regret and low-regret. Water UK (2016[cdxxxiv]) assessed a twin track approach of demand management coupled with appropriate development of new resources and potential transfers as being the most suitable strategy for providing drought resilience in the future. They estimated that total costs per annum for all potential future scenarios (under the Business As Usual base demand

management strategy) to maintain resilience at existing levels in England and Wales are between £50 million and £500 million per annum in demand management and new water resource options. If resilience to 'severe drought' is adopted, this increases to between £60 million and £600 million and for resilience to extreme drought, between £80 million and £800 million per annum. There are several studies that have looked at demand side measures for households that identify a large number of low and no-regret options. The study by Arup (2008[cdxxxv]) looked at a range of water saving measures, and estimated costs and pay-back times. A similar study was commissioned by the CCC (Davis Langdon, 2011[cdxxxvi]) looking at cost-effectiveness of alternative household options, and this was updated by Wood Plc (2019[cdxxxvii]) updating a previous cost-curve study.

These studies identify estimated measures with benefit to cost ratios above 1 for different house types, comparing new build vs. discretionary retrofit. The study provides unit-cost estimates for different measures, and calculated cost-curves to show their relative cost-efficiency. When considering wider benefits from a societal perspective (including avoided GHG emissions), additional no-regret measures are identified. Generally, end-of life upgrades and measures installed in new builds were more cost-effective compared to retrofits. These studies highlight the high economic benefits of further action.

H11: Risks to cultural heritage

<u>*CCRA3 Technical Report*</u>
This risk describes effects of climate change on cultural heritage, including moveable heritage (museum collections and archives), archaeological resources, buildings and structures, cultural landscapes and associated communities, and intangible heritage (folklore, traditions, language, knowledge and practices. Chapter 5 of the Technical Report identifies the impacts of climate change on cultural heritage are already occurring, and future climate change poses additional risks, especially for coastal heritage.

<u>*Valuation*</u>
Climate change has the potential to affect cultural heritage buildings in similar ways to outlined in H3 for floods (including coastal floods) and H5 for building fabric. This may affect physical assets, maintenance, repair, conservation, etc. These risks are likely to be particularly important for coastal cultural heritage.

The valuation of such impacts is very complex, as it should take into account both the economic and non-economic value of such assets. Heritage has important cultural, social and environmental values, i.e. non-use values, which can be further distinguished between *option*, *existence* and *bequest* value. *Option* value refers to the benefit from having the option of visiting a site; the *existence value* reflects the benefit people receive from knowing that a particular asset simply exists; and the *bequest* value is the value of satisfaction from preserving an asset for future generations. Such benefits are not provided by markets, making their estimation challenging. However, for unique assets such as heritage, the non-use values can outweigh use values, hence understating these values is very important for adaptation.

A literature review for this risk has found little information on the economic impacts of climate change on cultural heritage. This reflects the difficulty in understanding how climate directly affects cultural heritage, which is amplified by the fact that impacts are very site-specific. The current lack of (historical) evidence on how climate have affected cultural heritage to date makes it very challenging to make future projections of impacts, let alone try to value them. Further, the evaluation would need to estimate the costs of repairing damage (when possible) or the cost of protecting cultural heritage from being damaged across the UK – and these costs are not known.

It is also possible in economic research to estimate the value that people attach to cultural heritage can be estimated through survey methods which ask people to directly report their willingness to pay (WTP) to obtain a specified good, or willingness to accept (WTA) to give up a good. Such estimates can offer some insights into the total economic value of the benefits provided by cultural heritage, although these are clearly very site-specific. Several studies exist in the literature, whose findings can be applied in cost-benefit analyses (value transfer application), although to different extents. There are such studies in the UK (Eftec, 2005[cdxxxviii]), although the coverage is inevitably partial.

For example, Pollicino and Maddison (2002[cdxxxix]) used contingent valuation to gather information on WTP to increase the frequency of the cleaning cycle (from a 40-year cleaning cycle to a 10-year cleaning cycle) for the exterior of the Lincoln Cathedral. The cathedral suffered significant damage from air pollution. The report shows that the mean WTP of respondents in Lincoln itself was £49.77 per household per year, whilst from those outside Lincoln it was £26.77 (1998 prices), with an aggregate WTP figure of £7.3 million. In another study, Pollicino and Maddison (2004[cdxl]) report willingness to pay (WTP) for preserving, cleaning and restoring several historic buildings in Oxford ranging from £20 and £34 per year/household on average. Respondents' preferred intervention was the preservation option, by a considerable margin (76%). The study reveals that willingness to pay for different intervention strategies is shown to depend strongly on household income as well as on the scope of the intervention project. These studies indicate that there could be potentially a significant WTP to preserve cultural heritage against climate change.

Climate change will also affect temperature and humidity levels inside museums and galleries (Coelho et al., 2020[cdxli]), possibly leading to higher costs for guaranteeing the appropriate indoor climate for works. This can be addressed through temperature control, notably with cooling (as H6). The National Trust (2021[cdxlii]) has developed a map that illustrates the threat climate change poses to some of its most iconic and culturally significant sites. The map is drawn using a "worst case scenario" in which emissions continue their current trajectory. The map reveals that:

- The number of National Trust sites at high or medium risk of climate related hazards could increase from 20,457 (30%) in 2020 to 47,888 (71%) in 2060 out of a total 67,426 sites.
- The number of National Trust sites in the highest threat level area could rise from 3,371 (5%) to 11,462 (17%) in the same period.
- The number of National Trust scheduled monuments at high or medium threat risk are projected to increase from 1453 (27%) today to 3861 (72%) out of a total 5388 by 2060.

However, while this provides some numbers on the potential assets at risk, it does not provide quantification of the risk (damage) from climate change, and thus it is not possible to attempt valuation.

Cultural heritage is intrinsically linked to economic activity by supporting jobs and attracting tourism. In all but extreme cases, it is unlikely the cultural heritage will be lost, and more that it will be damaged. Given the evidence, it is extremely difficult to provide an indicative valuation for this risk, and thus is unknown (note, the CCRA3 Technical Report scored as a medium).

Table 79 Valuation of H11: Risks to cultural heritage.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Unknown	Unknown	Unknown	Unknown	Unknown	
England	Unknown	Unknown	Unknown	Unknown	Unknown	
N. Ireland	Unknown	Unknown	Unknown	Unknown	Unknown	
Scotland	Unknown	Unknown	Unknown	Unknown	Unknown	
Wales	Unknown	Unknown	Unknown	Unknown	Unknown	
Confidence						

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation
It is very challenging to estimate the costs and benefits of adaptation for cultural heritage, because of the heterogeneity. Costs are very site specific, and benefit analysis involve challenging valuation aspects, that included direct and wider economic benefits, but also non-use values, the latter including option, existence and bequest value. Further, in many cases, adaptation will be part of broader interventions targeting at risk areas, e.g. coastal or river flood management.

For particularly sensitive sites, there are options for monitoring and surveillance, in order to recommend both preventative and remedial action. There are also some limited examples in the international literature with case studies (ex ante and ex post), as well as willingness to pay studies that provide some estimates to compare against potential costs (for specific cultural heritage sites). For example, Pollard-Belsheim et al. (2014[cdxliii]) investigated the effectiveness of adaptation strategies to preserve coastal archaeological sites.

There are also some additional issues with the impact of climate change of artifacts inside museums and galleries. There is some evidence on the options for guaranteeing the appropriate indoor climate, which involve similar issues on the choice between mechanical or passive cooling. Coelho et al., (2020[cdxliv]) examined such examples and report passive retrofit measures are cost-effective, but again, adaptation effectiveness and will be extremely site specific.

H12: Risks to health and social care delivery

CCRA3 Technical Report
Chapter 5 of the Technical Report highlights the risks of damage to health infrastructure and equipment from flooding (river and surface water flooding), as well as problems from heatwaves for patients, staff and equipment in hospitals and care homes. The effects of extreme weather will also affect people's health and wellbeing, which will change demand for services.

Valuation
There are potential flood risks to health care buildings, and the Technical Report states that approximately 10% of hospitals are sited in areas of significant flood risk in the UK. There is not good evidence on the equivalent annual damage for these events, now and with climate change, but they could be potentially significant.

The Technical Report identifies that heatwaves cause problems with the functionality of hospitals as well as the thermal comfort of patients and staff. This will lead to increased costs of cooling (if such options are available), or increased discomfort and potentially additional health impacts for patients. There are also similar issues with care homes. In both cases, the potential health risks are higher given the age or vulnerability of patients. Indirectly, the raised health risk is included in H1, which is based on overall population estimates, and thus will include those in these settings. However, it is possible that climate change could lead to disproportionate increases in risks (over and above the projections in H1).

Given the lack of quantified evidence, it is very difficult to monetise this risk. This is therefore included as unknown (note, the CCRA3 Technical Report scored as a medium to high).

Table 80 Valuation of H12: Risks to health and social care delivery

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Unknown	Unknown	Unknown	Unknown	Unknown	
England	Unknown	Unknown	Unknown	Unknown	Unknown	
N. Ireland	Unknown	Unknown	Unknown	Unknown	Unknown	
Scotland	Unknown	Unknown	Unknown	Unknown	Unknown	
Wales	Unknown	Unknown	Unknown	Unknown	Unknown	
Confidence						

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation
As highlighted in the sections above, a particular issue is around heat risks, and thus there are similar issues on passive versus mechanical cooling options as for all buildings (see H1). There are obvious potential benefits from ensuring new care homes and hospitals are designed for the future climate. This is particularly important given the high risks and high lock-in involved, i.e. the higher costs of retrofitting later. There are also potential options for retrofitting existing care homes and hospitals.

There is some analysis of potential adaptation options for care homes (Curtis et al, 2014[cdxlv]: Gupta et al., 2016[cdxlvi]: PHE, 2018[cdxlvii]; Oikonomou et al., 2020[cdxlviii]). These identify a range of options, including care home operation (monitoring, early warning, emergency response), passive and mechanical cooling, and enhanced regulations, standards and guidance from care sector bodies and Government departments. Some initial work has been undertaken to explore a cost-benefit evaluation of building adaptations designed to protect against heat risks to residents of care homes in England (Ibbetson, 2021[cdxlix]). The work found that various physical adaptations have the potential to at least be cost-effective and reduce heat risk. For example, in one case study, external window shading was estimated to reduce mean indoor temperatures by 0.9°C in a 'warm' summer and 0.6°C in an 'average' summer. In this case, for a care home of 50 residents, over a 20-year time horizon and assuming an annual discount rate of 3.5%, the monetized benefit of reduced Years of Life Lost (YLL) would be between £44,000 and £230,000 depending on which life-expectancy assumption is used. Although this range represents appreciable uncertainty, it appears that modest cost adaptations to heat risk may be justified in conventional cost-benefit terms even under conservative assumptions about life expectancy and should therefore be considered as an important complement to operation responses.

Further investigation of the options would be highly beneficial. For hospitals, there is some literature on hospital design (including retrofitting) that emphasis passive approaches (Giridharan et al., 2013[cdl]: Fifield et al., 2018[cdli]) which highlight the potential benefits of such designs, but also highlights that other drivers, notably economics, are preventing uptake. However, the costs and benefits of actions, especially for retro-fitting existing buildings, will be very site specific.

H13: Risks to education and prison services

CCRA3 Technical Report
These risks primarily relate to risks of heat and flooding on educational and prison buildings, but also the potential effects on children and prisoners. Chapter 5 of the CCRA3 Technical report sets out that the evidence base for current and future risks is fairly limited, though there is most information on schools than prisons. High indoor temperatures have adverse effects on health and wellbeing, especially in young children.

Valuation
Climate change has the potential to affect educational buildings and prisons in similar ways to outlined in H3 for floods (including coastal floods) and H5 for building fabric, as well as in terms of heating and cooling demand (H6). These could affect physical assets, as well as operating and maintenance costs.

In 2007, floods resulted in school closures across England with a total of 400,000 pupil school days lost which was estimated to have an economic cost of £12 million, not including damage to property (EA, 2010).

Sayers et al. (2020) estimates the number of schools at risk of flooding, in the significant, moderate and low probability bands under future climate scenarios (tables below). The number of schools at risk is significantly higher in England, although this is expected given the higher population. However, there are no projections of the increase in school days lost to flooding under climate change, which makes it difficult to know how large this potential effect could be.

A further risk is associated with disruption, and in particular the high vulnerability of children, the youngest in particular. These include potential cognitive and learning issues, mental health consequences, and missed school days for children and work-days for educators as well as parents/carers. These impacts can be considered by the additional costs of addressing these risks (as a proxy for impacts), or through the direct estimation of the welfare impacts, i.e. lost time, medical costs and dis-utility. For the latter, there is insufficient information on the physical impacts of climate change on educational settings to allow valuation. However, to give a sense of the scale of impact, we report estimates for the June 2007 floods, which affected 467 schools in the Yorkshire and Humberside and led to 170,000 pupils losing a total of 400,000 school days. At an average expenditure per pupil day of £24.5 (2007the Environment Agency estimated the cost of 400,000 school days lost at £9 million (EA, 2010). To provide an indicative estimate of likely future costs, if 1% of the schools at significant risk under a 2˚C scenario in 2050 (i.e. 159 in the UK) would have to be closed due to flooding, with an estimated number of 360 pupils per school (57,240 in total), this would lead to some 134,514 school days lost. At a cost of £30.7 per pupil day (2020 prices)[20], this would be equal to costs worth £4m for one flood event only. It is worth noting that these costs do not include the costs of parents taking time off work with resultant loss of earnings and of the value of output associated with work-days. There could also be similar impacts through increased heat extremes, with impacts through lost school days or reduced learning, though again there are no numbers on which to base valuation.

If these effects are very severe and regular, they could lead to long-term drops in educational attainment, and thus future earnings. Such impacts have been valued in other contexts, notably the effect of lead pollution from vehicles and the effects on childhood IQ, and thus loss of earning potential. However, while valuation methods exist, there is a lack of data on the impacts of flood related disruption or heat exposure on learning, which means it is very difficult to value any potential effects.

Similarly, there are potential issues for prisons overheating. These would lead to a potential welfare impact on prisoners, in terms of discomfort (or in extreme cases, health impacts), or resulting increasing ventilation/cooling costs, though there is insufficient information to quantify or value these (note, the CCRA3 Evidence report scored as a medium, rising to high for England late century).

[20] Using a GDP deflator of 1.25. See https://www.gov.uk/government/statistics/gdp-deflators-at-market-prices-and-money-gdp-december-2020-quarterly-national-accounts

Table 81 Valuation of H13: Risks to education and prison services

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Unknown	Unknown	Unknown	Unknown	Unknown	
England	Unknown	Unknown	Unknown	Unknown	Unknown	
N. Ireland	Unknown	Unknown	Unknown	Unknown	Unknown	
Scotland	Unknown	Unknown	Unknown	Unknown	Unknown	
Wales	Unknown	Unknown	Unknown	Unknown	Unknown	
Confidence						

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

<u>Adaptation</u>

Schools. The general set of adaptation interventions for schools are similar to other buildings, although there are additional low regret options for behavioural responses and emergency plans. There is some specific information on potential options, and general affordability (e.g. GLA, 2020[cdlii]) as well as potential benefits (noting these include reduced cognitive and learning issues, mental health, and lost school days). Thomson et al. (2015[cdliii]) report on several projects under the Innovate UK's Design for Future Climate, Adapting Buildings (D4FC) programme, which included schools, with reported costs for adaptation measures. There is also some international literature which identifies the benefit to cost ratios for greening schools (Kats, 2003[cdliv]: 2006: Zhang et al., 2018[cdlv]) which report higher costs, but net benefits when considered on a life cycle basis. However, costs and benefits vary on a case-by-case basis, and between retrofits and new buildings.

Prisons. Again, there are a set of similar adaptation options for prisons, both non-technical and technical, with similar types of issues, i.e. building heterogeneity, retrofit versus new. The recent Ministry of Justice's Adaptation Plan (MoJ, 2020[cdlvi]) requires that sites assess risks and use this assessment to inform adaptation plans/actions, and a set of measures are recommended, but there is no analysis of costs and benefits. There is some information (Jewkes and Moran 2015[cdlvii]) on recently completed prison projects which are designed to meet the BREEAM Excellent standard and include some relevant information.

Summary

The summary of the health, communities and built environment theme are presented below. Note that some risks have been split out, as compared to the CCRA3 Technical report, to allow more disaggregated valuation (including coastal flooding in H2, energy demand for heating versus cooling in H6, air pollution from aeroallergens in H7 and household water supply, noting the latter overlaps with I8).

This theme includes some of the largest economic costs of climate change identified in the overall CCRA3 valuation analysis, but also some of the largest economic benefits (opportunities). This is because it includes risks for which there is high evidence, including several of the most studied risks in both quantitative and monetary terms, and because it has a number of risks that lend themselves to valuation, including for non-market impacts (for health).

There are very large monetary values associated with flooding (river, surface and coastal), extreme heat (on health and well-being) and increased cooling demand. These all individually have estimated costs of £billions/year. There is also a potentially very high magnitude for the impact of climate change on building fabric, though this is driven by storm risk, which is very uncertain.

At the same time, there are also very high benefits (opportunities) from the improvement in health and well-being from warmer temperatures, and from the reduced winter heating demand and energy use, which also potentially run to £billions/year.

It is critical, however, that these risks and opportunities are considered separately and not aggregated in monetary terms, even when they affect the same receptor (i.e. heating and cooling of buildings, health benefits and dis-benefits), because they require different adaptation responses.

There are a number of other risks which are assessed as having low or medium monetary values. These include risks from vector-borne disease (H8), air pollution (H7a), and food safety (H9).

There are a number of risks where the evidence is much lower, and where further investigation would be useful, because the risks could be potentially large. These include aeroallergens (H7b), cultural heritage (H11), health and social care (H12) and risks to education and prison services (H13).

There is also an important gap on how some of these risks and opportunities will interact with the Net Zero commitment. The most important issue is for the delivery of Net Zero households and the need for low carbon heating (from the combination of fuel substitution and energy efficiency, including insulation). Climate change will affect winter heating demand, and thus the level of heating demand, but it will also increase the risk of summer over-heating, which could be exacerbated in low carbon buildings. Further consideration of the economic costs and benefits of synergistic mitigation and adaptation policy and technology is a priority for this area.

Table 82 Summary of Economic Costs/Benefits for Health, Communities and Built Environment for UK.

Risk or opportunity	Present Day	2050s, on a to pathway stabilising at 2°C by 2100	2050s, on a pathway to 4°C at end of the century#	2080s, on a to pathway stabilising at 2°C by 2100*	2080s, for 4°C world at the end of the century#	Confidence
H1. Risks to health and wellbeing from high temperatures	Very high	Very high	Very high	Very high	Very high	Low – medium
H2. Opportunities for health and wellbeing from higher temperatures	Very high	+Very high	+Very high	+Very high	+Very high	Low - medim
H3. Risks to people, communities and buildings from flooding	Very high	Very high	Very high	Very high	Very high	Medium
H3a River and surface flooding	*Very high*	*Very high*	*Very high*	*Very high*	*Very high*	
H3b Coastal flooding	*High*	*High*	*High*	*Very high*	*Very high*	
H4: Risks to the viability of coastal communities from sea level rise	Low	Low	Low	Low	Medium	Low
H5: Risks to building fabric	High	High	High	Very High	Very High	Low
H6a: Opportunities from reduced winter household energy demand	Very high	+Very high	+Very high	+Very high	+Very high	Medium
H6b: Risks from increased summer household energy demand	High	High	High	High	Very high	Low
H7a: Risks to health and wellbeing from changes in air quality	Low	Low	Low	Low	Low	Low
H7b: Risks to health and wellbeing from changes in aeroallergens	Unknown	Unknown	Unknown	Unknown	Unknown	Very low
H8: Risks to health from vector-borne disease	Low to medium	Low to medium	Low to medium	Medium	Medium	Low
H9: Risks to food safety and food security	Low	Low - medium	Low - medium	Low - medium	Low - medium	Low
H10a: Risks to household water supplies	Medium	High	High	High	High	Low-Medium
H10b: Risks to water quality	Unknown	Unknown	Unknown	Unknown	Unknown	Very low
H11: Risks to cultural heritage	Unknown	Unknown	Unknown	Unknown	Unknown	Very low
H12: Risks to health and social care delivery	Unknown	Unknown	Unknown	Unknown	Unknown	Very low
H13: Risks to education and prison services	Unknown	Unknown	Unknown	Unknown	Unknown	Very low

Very high = £billions/year.
High = £hundreds of millions/year.
Medium = £tens of millions/year.
Low = £<10 million/year.

Business and Industry

The list of risks and opportunities considered in the CCRA3 Technical Report for the business and industry chapter are shown below:

Risk/Opportunity
B1. Risks to business from flooding
B2. Risks to business and infrastructure from coastal change from erosion, flooding and extreme weather events
B3. Risks to businesses from water scarcity
B4. Risks to finance, investment and insurance including access to capital for businesses
B5. Risks to business from reduced employee productivity due to infrastructure disruption and higher temperatures in working environments
B6. Risks to business from disruption to supply chains and distribution networks
B7. Opportunities for businesses from changes in demand for goods and services

The CCRA3 Technical Report (Chapter 6) uses a business function approach to look at the impacts of climate change on site location, capital, labour, supply chains, distributional networks and products and services. The valuation analysis here builds on this approach.

In previous assessments of the economics of climate change impacts (COACCH, 2018[cdlviii]), the business and industry sector has been identified as a particular gap, with a low coverage of valuation studies and estimates. However, there is more information available since the time of the CCRA1 valuation (Watkiss and Hunt, 2011), at least in terms of an understanding of the potential scale of impact or opportunity. There is also much more information emerging on physical climate risk, driven by initiatives such as the Task Force on Climate-related Financial Disclosures (2017[cdlix]), which is seeking to improve and increase reporting of climate-related risks, to help identify these and factor them into public and private sector decisions. This is likely to increase the information in this theme significantly in future years.

It is noted that several risks and opportunities in this theme have a strong linkage with other chapters. For example, some of the risks and opportunities in the natural environment chapter will affect businesses (e.g. agriculture, fisheries). Similarly, many of the impacts to infrastructure will have impacts on private companies (e.g. utilities, transport providers), including from cascading risks.

There is also a very strong linkage with the International theme, which arises because of the global nature of many supply chains. This means the risks to the private sector in the UK include a combination of domestic and international risks. There is also another international linkage, because the impacts of climate change will also affect other countries, and thus their comparative advantage relative to the UK. This can mean that international climate change impacts could lead to (potential) benefits for UK businesses. This chapter identifies these links, and tries to include them in the valuation analysis, while noting the need to avoid double counting of impacts across chapters.

The potential impacts of climate change on business

This valuation study looks at the impacts to private sector business and industry overall, there is no sectoral differentiation made between impacts on different types of businesses or in different locations. Climate change can potentially affect businesses, from the potential risk to assets (damage and loss), potentially leading to higher operating and maintenance costs, and/or lower revenues, which in turn can affect cashflow and subsequent company performance (profit and loss, balance sheet values) (Romain et al., 2018[cdlx]; de Bruin et al., 2019[cdlxi]).

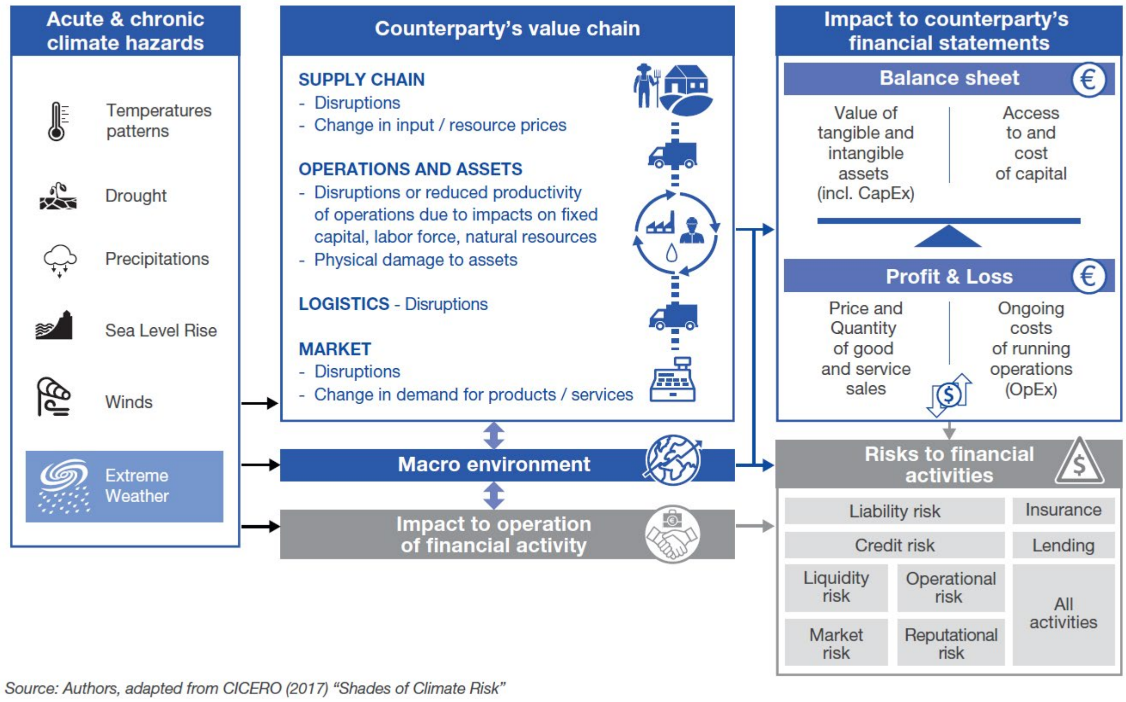

Figure 20 Propagation channels for climate risks through to the real economy and the financial sector. Source Romain et al., 2018

There is some early evidence on the size of these impacts. Recent reports have highlighted that climate change could reduce - on average – publicly listed companies' values by 2-3%, although the numbers vary greatly by sector (Economist, 2019[cdlxii]). This corroborates with Schroders' (2018[cdlxiii]) findings that found that insuring against physical risk could cost companies 4% of market values, with sectors such as oil and gas most affected.

In an analysis of 500 of the world's biggest companies by market capitalization (G500), 215 companies (representing US$16.95 trillion in market cap) provided estimations of the potential financial implications for a proportion of their reported risks, CDP (2019[cdlxiv]) estimated just under a trillion dollars (~US$970 billion) at risk. Over half of these risks were reported as 'likely / very likely / virtually certain' and likely to materialize in the short- to medium-term (around five years or earlier). The top four drivers of potential financial impact were identified as follows (CDP, 2019): increased operating costs (due to higher compliance costs, increased insurance premiums etc.) at ~US$179 billion; the write-off of assets or their early retirements because of potential damage to them / being in high-risk locations at ~US$170 billion; reduced demand for goods and / services due to a shift in consumer preferences totalling US$102 billion; and changes in policy leading to write-offs, asset impairment and early retirement of existing assets totalling ~US$73 billion. The financial sector was reported to be the most exposed to both physical and transition risk, with value at risk estimated at US$292 billion and US$400bn respectively. However, this sector was also the one which estimated the greatest opportunities from climate change, estimated at US$1.2 trillion (CDP, 2019).

Approximately 60% of companies headquartered in Europe identify substantive risks and opportunities related to climate change, with approximately US$640 billion in total estimated to be at risk, and of which transition risks account for almost US$400 billion (CDP, 2019).

This information does indicate potentially sizeable risks from UK impacts (noting risks to UK companies from overseas impacts is captured in the international risk, ID8), though, there is some duplication here with the risks of flooding estimated in B1 and B2, as this is likely to be one of the largest domestic risks to companies.

B1. Risks to business from flooding

The risks to businesses from flooding include the direct effects, from the flooding of business and industrial properties or sites (including the damage and loss of assets and contents), but also the indirect effects, from the costs of disruption, lost time or lost production, noting for large-scale events, these may have macro-economic effects on the economy. While the focus of this risk (B1) is on the disruption from flooding that occurs in the UK and affects business and industry located in the UK, these companies can also be affected by events that impact on supply chains, including internationally. The latter effects are discussed in the international chapter, under risks ID1 (food supply) and ID7 (international trade disruption), but are important to consider in looking at the overall risks to UK business and industry from climate change.

There are large reported costs to UK businesses from recent flood events. The Environment Agency estimated the costs of the winter 2015 / 2016 floods. The estimate of damage for business, i.e. for non-residential, business property damages was £513 million, with a range of £410 million to £616 million, based on ABI claims information (EA, 2018[cdlxv]). Large impacts were also reported for 2007 and 2012 floods. These are shown in the Table below. It is noted that the costs to business in 2015/16 were larger than costs to households, whereas in 2007 and 2013/2014 it was the other way around.

Table 83 Comparison of economic costs by flood event by impact category (2015 prices).

	2007 (summer floods) (£ million)	**2013 to 2014 (winter floods) (£ million)**	**2015 to 2016 (winter floods) (£ million)**
Residential properties	£1,500	£320	£350
Businesses	**£910**	**£270**	**£513**
Temporary accommodation	£120	£50	£37
Vehicles, boats, caravans	£98	£37	£36
Local authorities (excluding roads)	£170	£57	£73
Emergency services	£5	£3	£3
Flood risk management infrastructure and service	£24	£147	£71
Utilities (energy and water)	£398	£30	£104
Transport (roads, rail, air, ports)	£310	£295	£341
Agriculture	£59	£19	£7
Health	£340	£25	£43
Education	£14	£2	£4
Other (wildlife, heritage and tourism)	–	£13	£19
Totals	**£3.9 billion**	**£1.3 billion**	**£1.6 billion**

Direct damages can further be broken down into six components (MUL, 2020[cdlxvi]): building structure and fabric, building services, fixtures and fittings, clean-up costs, moveable equipment and stock. The literature shows that estimates of damage from flooding generally include either loss of assets or loss of activities and systemic disruption, but not always both.

Looking to future climate impacts, there is a relatively good evidence on the future effects of climate change in terms of the direct impacts from the national level analysis of floods, notably from the CCRA2 and CCRA3 research projects (Sayers et al., 2017[cdlxvii]: Sayers et al., 2020[cdlxviii]). The expected annual direct damages for non-residential properties[21] from all sources of flooding by UK country from these two studies are shown below.

The 2017 Sayers study is shown first below, showing the Expected Annual Damage, which is the mean economic damage over all possible flood return periods (averaging small damages from frequent flood events and large damages from rare events). Note this shows all flooding, including coastal, as well as river and surface. Note also that these figures assume a static socio-economic scenario, i.e. there is no economic growth or increase in non-residential properties assumed.

[21] Non- residential includes other buildings, not just businesses, i.e. some public buildings.

Table 84 Expected annual damage (EAD) for non-residential properties under different climate scenarios (£ and % increase relative to present day, no population change, current level of adaptation) (Source: Sayers et al. 2017).

EAD (£)	Present day	2020s		2050s		2080s	
		2ºC	4ºC	2ºC	4ºC	2ºC	4ºC
UK	**788,000,000**	**839,140,000**	**1,036,040,000**	**988,150,000**	**1,329,620,000**	**1,169,520,000**	**1,843,600,000**
England	590,000,000	631,300,000	784,700,000	743,400,000	991,200,000	879,100,000	1,357,000,000
		7%	33%	26%	68%	49%	130%
Northern Island	19,000,000	21,090,000	24,700,000	25,840,000	30,780,000	30,970,000	45,600,000
		11%	30%	36%	62%	63%	140%
Scotland	120,000,000	124,800,000	146,400,000	142,800,000	192,000,000	168,000,000	264,000,000
		4%	22%	19%	60%	40%	120%
Wales	59,000,000	61,950,000	80,240,000	76,110,000	115,640,000	91,450,000	177,000,000
		5%	36%	29%	96%	55%	200%

** Damage is estimated using the non-residential sector average WAAD that includes direct damages only.*
*** No change in non-residential properties is assumed under different population scenarios*

The 2020 Sayers study updates these figures. The total present day expected annual direct damages to non-residential properties from all sources of flooding in the UK is estimated at £670 million, which is lower than above. The expected annual damages for non-residential properties in the UK overall from Sayers (2020) are a projected increase (if current levels of adaptation continue) of 10% by the 2050s and 17% by the 2080s for a 2-degree; and 23% by 2050 and 42% by 2080, for a 4-degree scenario. Again, this assumes a static socio-economic scenario, i.e. there is no economic growth or increase in non-residential properties assumed.

Table 85 Expected annual damage (EAD) for non-residential properties (direct damage) under different climate scenarios (£ and % increase relative to present day, no socio-economic change, all sources of flooding, current level of adaptation (Source Sayers et al., 2020).

		2050		2080	
	Present Day	**2ºC pathway**	**4ºC pathway**	**2ºC pathway**	**4ºC pathway**
UK	**669,638,676**	**735,299,542**	**820,509,216**	**785,865,864**	**950,302,484**
		10%	**23%**	***17%***	**42%**
England	462,749,340	541,950,850	605,622,660	578,125,700	699,742,600
		17%	*31%*	*25%*	*51%*
Northern Ireland	41,827,540	49,285,776	55,606,040	53,547,528	64,838,924
		18%	*33%*	*28%*	*55%*
Scotland	114,130,064	96,491,544	106,800,584	102,190,784	122,908,384
		-15%	*-6%*	*-10%*	*8%*
Wales	50,931,732	47,571,372	52,479,932	52,001,852	62,812,576
		-7%	*3%*	*2%*	*23%*

It is stressed that there is considerable uncertainty around these numbers, associated with the climate model projections (and not just the scenario uncertainty, as in the table above). There are also further uncertainties around the hydrological models used, as well as the impacts. This uncertainty is not included in the Sayers analysis, but can be very large. For example, previous European flood studies e.g. Rojas et al. (2013[cdlxix]) find very large variation in the flood hazard change for the UK even for the same scenario, i.e. from analysis of different regional climate model outputs, with a range that can double (or halve) central ensemble values

Importantly, the Sayers CCRA3 analysis does not consider socio-economic change, i.e.it does not consider the increase in the number of business properties in the future. However, it does include such an increase for residential houses (see Risk H3) based on population growth. It also does not consider the potential increase in the value at risk (i.e. value of assets, business inventories, etc.) [22].

This means it implicitly assumes economic patterns remain as today, i.e. economic growth is not included[23]. This will significantly underestimate the impact of future climate change, because in reality, the increased flood hazard will impact on a larger business and industrial sector, with higher value assets, and likely more buildings at risk, from expected growth.

To address this, we have undertaken a sensitivity analysis by building in an uplift based on economic growth. A central GDP per capita (central population) multiplier uplift has been constructed (from 2020 to future time periods) by dividing GDP (central) projections by populations projections (also central) using the data from the CCRA research study on socio-economic projections (CE, 2019). The factor multipliers (1.9 and 3.4 for the two periods) have been applied to EAD figures for 2050s and 2080s respectively.

Table 86 Sensitivity analysis of expected annual damage (EAD) for non-residential properties (direct damage) under different climate scenarios with GDP uplift (£ and % increase relative to present day, no population change, all sources of flooding, current objectives for adaptation (Source Authors, based on Sayers et al., 2020 and uplift as described).

EAD (£)	Present day	2050s		2080s	
		2°C	4°C	2°C	4°C
UK	**669,638,676**	**1,340,364,454**	**1,495,691,652**	**2,608,536,741**	**3,154,353,761**
		100%	123%	290%	371%
England	462,749,340	987,912,563	1,103,978,772	1,918,981,595	2,322,666,456
		113%	139%	315%	402%
Northern Ireland	41,827,540	89,842,164	101,363,261	177,741,139	215,220,845
		115%	142%	325%	415%
Scotland	114,130,064	175,892,719	194,684,885	339,203,453	407,971,704
		54%	71%	197%	257%
Wales	50,931,732	86,717,008	95,664,734	172,610,553	208,494,757
		70%	88%	239%	309%

This shows the very high influence of socio-economic change on the results. This leads to much higher damages in the 2050s (approximately doubling current damage for the UK) and an even higher increase in the 2080s (approximately trebling current damage for a 2°C scenario and a factor of 4 for a 4°C scenario). This mirrors the findings of other international work, which record very high increases when climate and socio-economic futures are combined, e.g. Ward et al (2017[cdlxx]) for river flooding and Lincke et al. (2018[cdlxxi]) for coastal flooding.

There are other sources of information on this risk. The Environment Agency's National Flood Risk Assessment (NaFRA) takes into account the likelihood of flooding and potential consequences including for businesses. The Environment Agency estimates that the number of non-residential properties in England at medium and high risk of flooding are 81,588 and 34,822 respectively, representing 3.6% and 1.6% of all non-residential properties.

[22] At a more detailed level, future socio-economic change could change sectoral composition, or the location of premises, and this would also affect risks, but there is no information to assess the implications of these changes.

[23] The report says*: Important growth or changes (e.g. in the context of transitioning to a net zero economy) in non-residential properties or infrastructure could not be represented in this study due to a lack of reliable scenario data but should be considered in future analyses.*

All of the above information presents information for the direct impact. The actual damages will be larger, as they include indirect impacts, although there is less information available on these. To estimate the factor of increase in losses due to the indirect impacts of infrastructure disruptions, the UK Environment Agency has traditionally used an uplift factor of 1.7 in the previous Long Term Investment Scenarios (as reported by Sayers et al. 2015 for CCRA2) while some studies in the Thames Catchment have used a factor of 1.89 (Raynor, 2014). The Sayers report (2020) estimated indirect impacts for residential damages as being 70% of the direct damages plus intangibles assumed to be an additional 20% of the direct (residential) damages. It is possible to apply these values to the business flooding damages above as a sensitivity analysis. The addition of the 70% for tangible damages is added to the values above and presented in the table below. This indicates that when these effects are included, the damages are very large indeed.

Table 87 Sensitivity analysis of total (direct and indirect) expected annual damage (EAD) for non-residential properties under different climate scenarios, with and without GDP uplift (£ and % increase relative to present day, all sources of flooding, current objectives for adaptation (Source Authors, based on Sayers et al., 2020 and uplift as described).

EAD (£) UK	Present day	2050s		2080s	
		2ºC	4ºC	2ºC	4ºC
Sayers et al., CCRA3 (2020)	669,638,676	735,299,542	820,509,216	785,865,864	950,302,484
+ indirect damages	1,138,385,749	1,250,009,221	1,394,865,667	1,335,971,969	1,615,514,223
Sayers et al + socio-economic growth	669,638,676	1,340,364,454	1,495,691,652	2,608,536,741	3,154,353,761
+ indirect damage	1,138,385,749	2,278,619,572	2,542,675,808	4,434,512,460	5,362,401,394

There is one recent study that provides some support for the magnitude of these indirect costs, and even indicates in some cases these indirect impacts could be higher. Impacts on business sites can be compounded by the impacts on infrastructure that allow access to a site or allow it to operate. Koks et al. (2019) used geospatial information on the location of electricity infrastructure assets and local industrial areas and employed a multiregional supply-use model of the UK economy to trace the impacts of floods of different return intervals across 37 subnational regions of the UK. The authors used the loss in labour productivity (temporary reduced employment) as the proxy for business disruption. The results show up to a 300% increase in total economic losses when power outages are included in the risk assessment, compared to analysis that just includes the economic impacts of business interruption due to flooded business premises (Koks et al.,2019). The authors estimated that the total economic loss resulting from failure of five substations (worst case scenario) to be around £27 million per day. Note, however, this overlaps with risk I1 (cascading risks).

Koks et al (2019) report that the estimate of 3 in their study (compared to 1.7 in LTIS) is higher because most of the existing estimates do not account for the macroeconomic impacts and are generally underestimating indirect impacts (Koks et al. 2019).

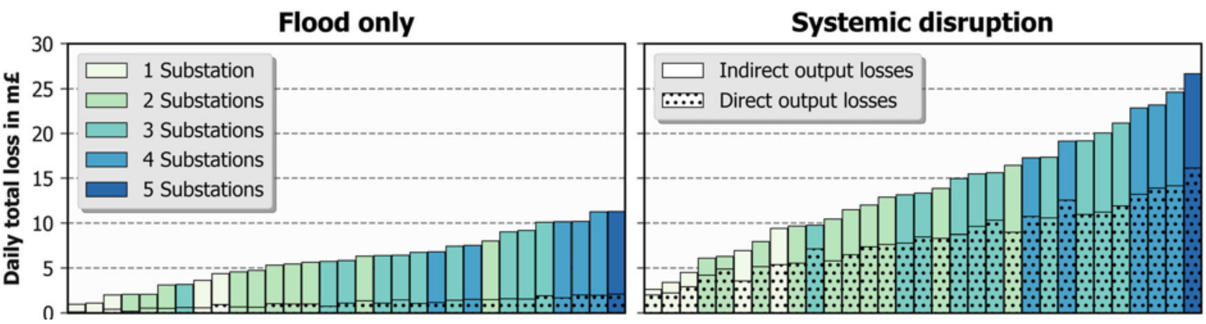

Figure 21 Total daily output losses for the United Kingdom for 31 failure combinations.

The left panel shows the impacts due to a flood with a return period of 1/1000. The right panel shows the impacts due to a flood with a return period of 1/1000 and a failure of the electricity substation at the same time (Source: Koks et al. 2019).

Previous studies have looked at the implications of low likelihood, high impacts, associated with extreme sea-level rise (SLR) or high ++ scenarios, which include scenarios > 1 metre SLR. Sayers 2017 reports a very high increase under such scenarios for non-residential EAD, with a 220% increase in the 2050s (compared to a 69% increase with a 4°C scenario) and a 410% in the 2080s (compared to a 140% increase with a 4C° scenario).

The inclusion of economic multipliers and/or indirect factors does increase the current and future damages into the very high scoring (billions per year) at the UK level and for England. As highlighted above, these are for central projections and there is a considerable range from the climate and hydrological models. The values are shown for current adaptation scenarios.

Table 88 Valuation of B1. Risks to business from flooding. Central projections. Current adaptation.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Very high	Very high	Very high	Very high	Very high	Very high
England	Very high	Very high	Very high	Very high	Very high	
N. Ireland	High	High	High	High	High	
Scotland	High	High	High	High	High	
Wales	High	High	High	High	High	
Confidence	High	High	High	High	High	Medium

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Finally, there is also information on how these numbers change with adaptation assumptions. The Sayers report presents values with different levels of adaptation. These are shown below for the UK. They include three scenarios:

- No additional action. This is a counterfactual scenario with low levels of adaptation, assuming that existing flood protection is maintained, but there is no future additional adaptation, i.e. investment in conventional defences fails to keep pace with climate change.
- Current objectives and current adaptation. This assumes flood risk management policies continue to be implemented as in the recent past whilst taking on board anticipated changes that are likely to result from recent changes in policy. While current policies are in line with this scenario, they imply high levels of future costs, e.g. Defra expect expenditure of at least £1 billion per year for England (as recommended from Long-Term Investment Scenarios).
- Enhanced whole system adaptation. This goes beyond the current implementation of policy (and recently introduced policy) with implementation in-line with a higher level of ambition.

Table 89 Expected annual damage (EAD) for UK non-residential properties (direct damage) under different adaptation scenarios (£, all sources of flooding, direct values, no socio-economic change. (Sayers et al., 2020).

EAD (£) UK	**Present day**	**2050s**		**2080s**	
		2°C	**4°C**	**2°C**	**4°C**
No additional action	669,638,676	848,665,072	965,060,992	936,878,060	1,172,446,694
Current objectives	669,638,676	735,299,542	820,509,216	785,865,864	950,302,484
Enhanced whole system adaptation	669,638,676	634,643,310	704,142,866	676,375,200	806,916,404

This shows even with adaptation in place, there are still significant levels of residual damages (albeit lower than the baseline), and a significant increase in flood damages from current. If the GDP uplift is included, as well as indirect costs, these future damage costs still increase, but the absolute benefit (in £) of adaptation will be greater.

Adaptation

The overall benefits of further investment in flood management for commercial property through the reduction in expected annual damages are estimated by Sayers et al. (2020[cdlxxii]). This study does not estimate the costs of these measures, and thus does not undertake a cost-benefit analysis, but the literature in general reports high benefit to cost ratios from such investment (Rojas et al., 2013[cdlxxiii]; Ward et al. 2017[cdlxxiv]).

In addition to protection, there is a role for raising awareness on climate risks (flood alerts) and providing relevant information and response planning. There is now a reasonable evidence base on the costs and benefits of property resilience and resistance measures for households (including Royal Haskoning DHV (2012[cdlxxv]); EA (2015[cdlxxvi]); and Wood Plc (2019[cdlxxvii]). The latter found that a number of flood resilience and resistance measures could be considered no-regret adaptation measures (i.e., a benefit to cost ratio of greater than one in cases where there is a greater than 1% chance of Annual Exceedance Probability, AEP). In general, this literature reports that all measures are more expensive if retrofitted rather than installed in new builds. For resistance measures, the difference between costs of retrofitting vs. incorporating into new builds are more modest. However, the applicability of each of these measures depends on the type of flooding (recurrence and depth), as this alters the relative cost-effectiveness (and benefit to cost ratio). While there is less data on the costs and benefits of similar measures for commercial properties, it is likely that similar findings of low-regret adaptation opportunities apply. Given the residual damage costs even with current flood management policy (Sayers et al., 2020), this is an area where there are benefits of future action.

B2. Risks to business and infrastructure from coastal change from erosion, flooding and extreme weather events change

The CCRA3 Technical Report (Chapter 6) identifies that the impact to coastal business locations is mainly driven by coastal flooding and extreme weather events, rather than coastal erosion. However, there is evidence from the CCC coastal change report that sea level rise could lead to the loss of coastal business locations and the infrastructure they rely on, for example, where these involve access, power and communications. The valuation analysis has investigated these risks. It is stressed that B1 (above) includes coastal flooding, so it is important to avoid double counting.

The Government Office for Science and Foresight (2017[cdlxxviii]) analysis (based on earlier data from Sayers) reported that at present day 79,000 non-residential properties (NPRs) are exposed to the severe risk of coastal flooding (1-in-75 or greater), with expected annual damage (EAD) estimated just below £190m for non-residential properties. The greater risk for NRPs was in England (~80% of current EAD or £149m), followed by Scotland (£20m or 10%), Wales (£18m or 9%), and Northern Ireland (£2m or 1%). Estimates were presented for the 2080s, with EAD (direct costs, no population change) for NRPs estimated to increase by 58% under a 2^{o}C scenario (corresponding to ca. 30 cm global mean sea level rise from 1990 to 2100), and 182% under a 4^{o}C scenario (corresponding to ca. 60 cm global mean sea level rise from 1990 to 2100).

The CCC's Coastal Change Report (CCC, 2018[cdlxxix]) reports a total of 144,985 non-residential properties in England within Flood Zone 3, which represents the present day 1:200 (0.5%) year risk from coastal flooding.

The Sayers et al. (2020) CCRA3 research estimates the total present day expected annual direct damages to non-residential properties from coastal flooding in the UK at £120 million. Expected annual damages for non-residential properties at risk from coastal flooding across the UK in 2050s and 2080s are estimated under a 2˚C scenario at £145m and £181m respectively, and under a 4˚C scenario at £181m and £234m respectively. Note that these coastal flooding values are already included in the Tables in risk B1 above, and are presented here to show the contribution of this risk only.

Table 90 Expected annual damage (EAD) for coastal flooding for non-residential properties (direct damage) under different climate scenarios (£ and % increase relative to present day, no socio-economic change, current level of adaptation). (Source: Sayers et al. 2020).

EAD (£)	**Present day**	**2050s**		**2080s**	
		2ºC	**4ºC**	**2ºC**	**4ºC**
UK	**120,400,117**	**144,638,200**	**180,730,895**	**180,743,412**	**234,056,293**
		20%	*50%*	*50%*	*94%*
England	79,318,890	109,135,320	139,986,460	140,968,990	184,242,720
		38%	*76%*	*78%*	*132%*
Northern Ireland	1,668,363	2,273,911	3,684,419	3,239,262	4,791,753
		36%	*121%*	*94%*	*187%*
Scotland	19,970,272	16,957,896	18,952,168	18,442,796	22,657,564
		-15%	*-5%*	*-8%*	*13%*
Wales	19,442,592	16,271,073	18,107,848	18,092,364	22,364,256
		-16%	*-7%*	*-7%*	*15%*

As in B1, it is noted that the Sayers CCRA3 analysis does not consider socio-economic change. To assess this, we have considered a sensitivity analysis by building in an uplift based on economic growth. A central GDP/per capita (central population) multiplier uplift has been constructed by dividing GDP (central) projections by populations projections (also central). As with B1, there would be further damages if indirect effects are included. In Sayers, indirect damages are assumed to be 70% of the direct damages, and are added on top of direct damage estimates for residential and non-residential. They are therefore excluded from the uplift calculations. Again, the coastal flooding values int the Table below are already included in the Tables in risk B1 above.

Table 91 Expected annual damage (EAD) for coastal flooding for non-residential properties (direct damage) under different climate scenarios with GDP uplift (£ and % increase relative to present day, current level of adaptation). (Source: Sayers et al. 2020).

EAD (£)	**Present day**	**2050s**		**2080s**	
		2ºC	**4ºC**	**2ºC**	**4ºC**
UK	**120,400,117**	**263,658,401**	**329,451,133**	**599,944,408**	**776,906,680**
		119%	174%	398%	545%
England	79,318,890	198,940,833	255,178,827	467,920,553	611,559,716
		151%	222%	490%	671%
Northern Ireland	1,668,363	4,145,072	6,716,261	10,752,133	15,905,340
		148%	303%	544%	853%
Scotland	19,970,272	30,912,247	34,547,570	61,217,459	75,207,603
		55%	73%	207%	277%
Wales	19,442,592	29,660,249	33,008,474	60,054,264	74,234,022
		53%	70%	209%	282%

What all these studies show is the increase with the level of SLR over time and with higher warming scenarios. The number of non-residential properties at risk rises with sea level.

This is important considering the higher estimated SLR in the IPCC SROCC (2019), and UKCP18. There is also the potential for more extreme SLR, including the low likelihood high impact scenarios that have been identified by recent global expert elicitations (Garner et al., 2018[cdlxxx]; Bamber et al., 2019[cdlxxxi]), which raise the possibility of even higher increases under high-emission scenarios, with conceivably 2 metres by 2100. While CCRA3 did not include a high++ analysis, the sensitivity analysis for CCRA2 (Sayers, 2017) shows that extreme sea level rise (>1m) would increase these numbers very significantly (by a factor of 2 in the 2050s and 4 in the 2080s).

Number of properties and area potentially affected assuming the absence of vulnerable defences and 'what-if' values of sea level rise in England (Source: Sayers et al. 2015)

Sea level rise (m)	Length of defences at risk (km)	Percentage of coastal defences at risk	Residential properties	Non-residential properties	Area (km^2)
0	110	10	86 000	36 000	580
0.5	190	18	220 000	92 000	1 700
1.0	220	21	290 000	120 000	2 100
1.5	280	27	390 000	150 000	2 700
2.0	340	32	510 000	210 000	4 100

Note: The Table above simply provides 'what if' values – no suggestion is made regarding the likelihood of the values provided for SLR, or the timescales by when they could potentially occur.

The summary values for coastal flooding are shown below. Again, it is stressed that the coastal values are already included in B1. The values in the table assume socio-economic growth is included. If indirect damages were also included, they would be higher, and in some cases, would tip the ratings upwards to the next category (i.e. from medium to high).

Table 92 Valuation of B2 –risks to business and infrastructure from coastal change from flooding and extreme weather events change.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	High	High	High	High	High	High
England	High	High	High	High	High	High
N. Ireland	Low	Low	Low	Low	Low	
Scotland	Medium	Medium	Medium	Medium	Medium	
Wales	Medium	Medium	Medium	Medium	Medium	
Confidence	High	High	High	High	High	Medium

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

There is also evidence on the influence of adaptation on these values. Coastal management policy is formalised through the Shoreline Management Plans (SMPs). These are non-statutory policy documents which inform wider strategic planning.

In 2018, the Government published a policy statement on Flood and Coastal Erosion Risk Management (FCERM), setting out government's future expectations for managing flood risk. In theory, these will reduce down potential impacts above, however, current coastal management plans are deemed not to be realistic (CCC, 2018), as they are not backed up by funding or legislation. Moreover, it seems likely that financial resources will not be sufficient in the future to defend the entire coast of England, Northern Ireland, Wales and Scotland, and so priorities are needed to allocate resources for coastal protection. In cases where there is no implementation of adaptation, this can create significant negative economic consequences.

Sayers et al (2020) does consider different adaptation scenarios (see B1 for descriptions). If levels of adaption are enhanced, expected annual damage is expected to diminish significantly, as shown in the table below. However, high levels of residual damage are still expected. For Northern Ireland in particular, even higher levels of adaptation are not expected to reduce EAD significantly compared to a scenario where the current level of adaptation continues. Note these values do not include socio-economic change or indirect damage, which would significantly increase the values.

Table 93 Expected annual damage (EAD) from coastal flooding for UK non-residential properties (direct damage) under different climate scenarios (£ and % increase relative to present day, no socio-economic change, all sources of flooding, for different adaptation assumptions. (Sayers et al., 2020).

EAD (£) UK	**Present day**	**2050s**		**2080s**	
		2ºC	**4ºC**	**2ºC**	**4ºC**
No additional action	120,400,117	177,476,435	236,600,752	236,626,925	336,401,801
Current objectives	120,400,117	144,638,200	180,730,895	180,743,412	234,056,293
Enhanced whole system adaptation	120,400,117	126,078,728	152,974,522	152,626,694	190,708,564

Erosion. In England, CCRA2 and the CCC's report on coastal adaptation (CCC, 2018; Jacobs et al., 2019[cdlxxxii]) it is reported that around a third of the English coastline is subject to erosion, which can be exacerbated by heavy or prolonged rainfall, coastal storms or sea-level rise. In Scotland, the National Coastal Change Assessment (NCCA), and Dynamic Coast programmes, have mapped the physical susceptibility of the coast and identifies that soft coastline (i.e. coast with the potential to erode) makes up 19% (3802 km) of the coast (Hansom et al., 2017[cdlxxxiii]). It estimates that between a half and a third of all coastal buildings, roads, rail and water network lie in these erodible sections (in Scotland, 78% of the coast is considered 'hard or mixed', and is unlikely to erode at perceptible rates, 19% is 'soft/erodible', whilst 3% has artificial protection.)

However, there is no economic valuation of these risks. There are some aggregate models which include coastal erosion, such as the DIVA model, which includes UK analysis (Brown et al., 2011[cdlxxxiv]). These indicate coastal erosion damage costs are much lower than direct flood costs (i.e. as captured in risk B1 and B2 above). On this basis the magnitude scores are given below, though it is stressed that these are only indicative.

Table 94 Valuation of B2 – Additional risks to business and infrastructure from coastal change from erosion – i.e. impacts over and above coastal flood risks included in B1.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Medium	Medium	Medium	Medium	Medium	Not known
England	Medium	Medium	Medium	Medium	Medium	
N. Ireland	Low	Low	Low	Low	Low	
Scotland	Low	Low	Low	Low	Low	
Wales	Low	Low	Low	Low	Low	
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

The overall benefits of further investment in coastal flood management for commercial property – and the reduction in expected annual damages and estimated in the Sayers *et al.* (2020), but the study does not estimate the costs of these measures, and thus does not undertake a cost-benefit analysis. In general terms, the literature reports that coastal adaptation is an extremely cost-effective response, significantly reducing residual damage costs to very low levels (Hinkel *et al.,* 2014[cdlxxxv]: Lincke et al. 2018[cdlxxxvi];), however, in rural areas, such measures often have benefit-cost ratios lower than one.

B3. Risks to businesses from water scarcity

While household consumption dominates the demand for water, some water resource zones have high non-household public water supply demand reflecting the nature and intensity of local industry and businesses. Water is used by business for a wide range of purposes, including (Defra, 2013[cdlxxxvii]):

- Industrial and manufacturing processes (including power generation), as an input or for cooling;
- Cleaning, sometimes for essential hygiene or safety purposes, for control of nuisance (such as dust suppression), or for aesthetics of clean vehicles and buildings;
- Irrigation to improve the yield and quality of crops;
- Drinking, by both people and animals, and for food preparation, for both people and animals, within industry and catering; and
- Navigation in canals and rivers, and for fish husbandry.

Businesses and industries need water in order to maintain supply chains and production lines. For businesses, the potential effects can vary between short interruptions to production processes to complete disruptions of supply chains. In some cases, a reduction in water volume would mean that the process capacity has to be de-rated or shut down. For example, nearly all food and beverage processing businesses need a constant supply of water. Other relatively large abstractors include mining and quarrying, and also entertainment and recreation. There are some differences among devolved administrations. In Scotland, for example, the chemicals and food and drink manufacturing sectors are large industrial users of water. In Northern Ireland, abstractions for general industrial purposes are mainly for food and drink production, and mining and quarrying.

The evidence base on water scarcity is more focused on public drinking water, which provides some indications of the risk to business. This was presented in detail in the Health chapter (H10: Risks to household water supplies) and also includes in the infrastructure chapter (I8. Risks to public water supplies from reduced water availability). In summary, HR Wallingford (2015) undertook a study for the CCRA2 that assessed the potential impact of climate change on public water supply (the supply-demand balance) at the end of the 25-year water company resource planning horizon. This was updated in 2020, as part of the CCC research projects for CCRA3 (HRW, 2020[cdlxxxviii]).

This estimated that the UK as a whole is currently in surplus of around 950 Ml/d. Looking to the future, HRW (2020) provides supply-demand balance, deployable output and water demand for the four countries of the UK. This shows that household consumption accounts for more than half of the demand for public water supplies across the UK, and leakage and non-household demand are of a similar magnitude and account for a little over 20% of demand in each country.

Table 95 Main components of baseline (~2019/20) supply-demand balance, deployable output and demand in the four countries of the UK (Source: HRW, 2020).

Country	Supply-demand balance (Ml/d)	Deployable output (Ml/d)	Water Available for Use	Demand Ml/d (% of total demand)					Target headroom
				Household	Non-household	Leakage	Other	Total demand	
England	400	16,250	15,150	7790 (56%)	2830 (20%)	2940 (21%)	320 (2%)	13,880	870
Wales	80	1,060	1,010	460 (55%)	180 (21%)	170 (20%)	20 (2%)	840	90
Scotland	300	2,260	2,340	830 (44%)	410 (22%)	590 (31%)	60 (3%)	1,890	150
Northern Ireland	170	840	770	290 (51%)	110 (19%)	160 (28%)	20 (4%)	570	30

HRW (2020) projects the supply-demand balance (Ml/d) in the mid-century (central population and no additional adaptation action) and for the late century, including climate change. In the mid-century, the UK is projected to face a supply-demand balance deficit of between -650 and -920 Ml/d. The vast majority of this impact is in England. There is a difference in climate change impact between 2°C and 4°C worlds, which is around 270 Ml/d at a national level. In the late century, there is a wide range of possible projections, but the deficit across the UK as a whole is projected to be between around 1,220 and 2,900 Ml/d (2°C to 4°C range, though the full uncertainty range is much higher). The deficit is again driven by England. The Wales region, Northern Ireland and Scotland all maintain a surplus supply-demand balance. However, the combined surplus is not sufficient to counteract the deficits located in England even if the infrastructure to transfer the water was available (and note this would have important additional costs). The projected impact of climate change on the supply-demand balance at the UK scale is around 40% of the potential projected impact of population growth.

HRW (2020) also conducted an analysis to estimate the potential surplus or deficit in water at a catchment scale. The results include estimates of the water resource available naturally (i.e. without the influence of abstractions or discharges) and whether existing environmental flow requirements are achievable given the potential for change in the natural flows in the future. Where unachievable, this is referred to as negative available resource, with impacts for abstractors as well as the environment. The study found that projected changes in river flows at Q95[24] across the UK are of the order of 0-20% reduction by the mid-century in a 2°C world everywhere except the western highlands in Scotland (where flows increase). In a 4°C world, this reduction increases (up to 30% flow reduction by mid-century) in some areas, such as Wales, the Severn and Tweed river basins; and il late-century could be in the order of 0-50% reduction across the UK. The study also estimated that should environmental flows remain fixed at the same absolute volume that they are today, many of the catchments across England, Wales, some in Scotland and one in Northern Ireland would be unable to meet their environmental flow requirements without the addition of discharges to the river network. Catchments at risk of negative available resource tend to be along the west coast of Great Britain, with catchments in Wales being affected the most. In the late-century (4°C world, central population projection and current and announced adaptation scenarios) 74 catchments across the UK, many in Wales plus others in the south west of England, far north of England, and western Scotland, are projected to have negative resource availability. This is 52 more than in the mid-century. Under fixed environmental flow scenario, 60 catchments are projected to be in deficit. Projected changes in river flow will influence the naturally available resource at Q95 that is available for both large and small abstractors (i.e. those with and without abstraction licences), and will impact business that rely on their own abstraction licenses rather than the public water supply.

There are, however, no economic valuation estimates in the HRW study. This study has therefore reviewed the literature. Many water companies conduct evaluations of their customers' willingness to pay to avoid or reduce the risk of disruptions, increase water quality etc. to inform their Price Reviews (PRs). However, these evaluations often have a strong focus on residential customers, and WTP estimates for businesses were not found for this study.

The National Infrastructure Commission (NIC, 2018[cdlxxxix]) estimated the costs of supplying water during drought to avoid imposing emergency restrictions to businesses and households on essential use (i.e. rota cuts). The total costs between 2020 and 2050 of implementing emergency measures to provide household water supply during a 0.5% drought, weighted by the probability of occurrence, ranged between £13 and £16 billion, depending on the assumed climate and population growth. The total costs over the same period of implementing emergency measures against a 0.2% drought range between £21 billion and £27 billion (NIC, 2018). However, these values do not show the costs for business use separately.

There has been some work to estimate the impact of droughts on businesses. In a report prepared for Defra in 2013, the impacts of the 2012 drought in England were estimated (Defra, 2013[cdxc]). During that drought, water companies introduced temporary use bans to restrict demand. These restrictions applied in some areas in the second quarter of 2012. As the main target of temporary use bans, households were affected, together with businesses offering services to domestic customers, in particular landscaping services and the horticultural trade. With respect to the impacts on the economy, economic costs were estimated at £165 million in revenues and £96 million in profit. Vivid

[24] The river flow that is equalled or exceeded for 95% of the time. Q95 is a common low flow reference (and conversely, Q10 is a high flow reference). In HRW (2020), Q95 refers to the 30-year annual average Q95.

Economics (for Defra, 2013) also estimated the impact that an extended drought scenario could have had on key sectors such as public water supply companies and agriculture, as well as sports turf (golf) (i.e. they looked at a what if scenario if the drought had continued into a third dry winter). By assuming that management actions taken during the 2011/12 drought would have been applied for the extended period, the study estimated that cumulative “first round” turnover losses would have amounted to just under £2.9 billion over the two year period, equivalent to 6% of the total turnover under business as usual; and cumulative first round profit losses would have amounted to just under £1.46 billion over the two year period, equivalent to 7% of the total profit under business as usual.

A consultation reported in AECOM (2016) suggested that in a severe drought situation, where private supplies became unavailable or were restricted, the majority of abstracting firms would attempt to switch to private water supplies (PWS) as long as such supplies were available. AECOM also found that if PWS back-up supplies were unavailable, most firms did not have a contingency plan in place to allow them to continue to produce with a reduced private water supply, which would imply a fall in production at such locations and for the period when private water was unavailable. Estimates of the economic costs[25] for a number of hypothetical drought scenarios differing in duration, severity and in decade of occurrence were estimated by AECOM (2016) to range from £261 million in a one-year severe drought in 2010s to £43,500 million in three-year extreme drought in 2050s[26]. Some data for specific locations are also available, although with limitations[27]. The costs of a severe drought to London’s economy were estimated by Thames Water to be up to £330m/day – due to the closure of schools and offices, as well as damage to wildlife caused by the introduction of severe water use restrictions resulting in supplies being cut off for part of the day or supplied at very low pressures[cdxci]

The empirical evidence on the 2012 drought suggests that these risks to businesses could therefore be significant for England, and these values, along with the supply-demand balance deficit, are used to provide indicative valuation scores, presented below. Note that while individual events could be very large, the annualised values are likely to be lower.

There is some additional information from UKCP18 on the potential for large multi-year droughts, that would comprise a low likelihood, high impact extreme. Based on the extended drought analysis from Defra, this would be a very high event, i.e. £billions. Looking ahead, moving towards a Net Zero target could have implications also for the water sector, e.g. changing the energy mix could affect the demand for water (see Chapter 4).

Table 96 B3. Risks to businesses from water scarcity.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
England	Medium	High	High	High	High	Very High
N. Ireland	Low	Low	Low	Low	Low	Low
Scotland	Low	Low	Low	Low	Low	Low
Wales	Low	Low	Low	Medium	Medium	Low
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

[25] The model examines the impact of a period of drought on industry, agriculture, the service sector and households.

[26] The socio-economic impacts are from demand restrictions due to standpipes and rota cuts. AECOM analysis has estimated the costs of drought modelled on a medium emissions climate change scenario. The 2050s do not consider the potential for businesses and households to implement adaptation measures that enhance their resilience to drought events. Given this, the results for these scenarios should be considered to represent an upper bound estimate (AECOM, 2016).

[27] For example, to estimate the economic impact on businesses, AECOM (2016) assume that profit is linearly impacted by the water reduction, that is, a 10% reduction in water availability causes a 10% reduction in profit; a 20% reduction implies a 20% impact on profit, and so on. In practice, the relationship between water availability and profit is likely to be non-linear (AECOM, 2016).

Adaptation
There are studies which have considered the overall costs and benefits of national level action to reduce the risk of water scarcity. There are also a complementary set of demand side measures that can be introduced by businesses, many of which are no-regret and low-regret. As a general rule of thumb, reductions of 30% in water bills are usually achievable at little or no cost for sites that have not previously tried to save water, and as much as 50%, or more, if projects with capital investment payback periods of up to two years are included (WRAP, 2005[cdxcii]). There are detailed cost-effectiveness assessments of measures for industrial sites, with indications of costs and payback periods.

B4. Risks to finance, investment and insurance including access to capital for businesses

As highlighted in the introduction, there is a growing recognition that climate change is a financial risk. The Task Force on Climate-related Financial Disclosures (2017[cdxciii]), established by the G20's Financial Stability Board, is seeking to improve and increase reporting of climate-related financial information, to help identify these risks and factor them into public and private sector decisions[28]. Alongside this, many of the world's Central Banks, including the Bank of England, are involved in an initiative to ensure the financial system is resilient to these risks, under the Network for Greening the Financial System (NGFS, 2019[cdxciv]). In 2020, the Bank of England (2020[cdxcv]) reported that there is clear evidence that banks, insurers, and the financial system will be impacted by climate change and the transition to a carbon-neutral economy.

The TCFD identifies that climate change can have two types of risks, arising from climate change impacts (physical risks) as well as changes in policy, legal, technology, and market changes from the transition to a low-carbon economy (transition risk). The focus here in CCRA3 is on physical climate risks.

The UK is potentially highly exposed to these risks, partly because of the direct risks to the UK, but also because the UK is a global financial hub, and thus subject to impacts internationally, though these are also captured in the International risks later as well, in ID8. There are a number of different elements:

- Risks to the financial sector;
- Insurance risk, including insurance affordability;
- Opportunities for the UK financial sector (note overlaps also with B7).

Risks to the financial markets
The physical risks to financial sector companies are largely captured in the other risks in this chapter, i.e. flood risks, over-heating, etc. However, climate change may also affect the financial sector through other pathways, affecting its operations, services, investments, etc. Some of these risks will arise from climate change impacts in the UK (and on UK investments) and some will arise from overseas impacts and thus on UK held international investments. Much of the risk is associated with the latter, and this overlaps with risk ID8 (international).

The UK is currently the leading exporter of financial services across the world. In 2018, The UK's financial services trade surplus of $82.7billion (equivalent to £61.9 billion) was nearly the same as the combined surpluses of the next two leading countries (the US and Switzerland) (The CityUK, 2019[cdxcvi]). This presents both risks and opportunities for the UK financial markets. It does mean that the UK is one of the most exposed countries to climate change due to its high financial leverage and high centrality in the global financial network. This has been demonstrated in a recent study from Mandel et al (2020[cdxcvii]), which estimates the overall direct and total impact induced by a 95th percentile coastal flood event (yearly damages). Losses are calculated for the financial and private

[28] It is also noted a new Taskforce on Nature-related Financial Disclosures has been created to provide a framework for corporates and financial institutions to assess, manage and report on their dependencies and impacts on nature, with a view to redirecting global financial flows away from nature-negative outcomes and towards nature-positive outcomes. Reporting frameworks will be developed in 2021, and tested early in 2022 before being made available worldwide.

sectors following a shock for two scenarios that combine climate and socioeconomics: First, a scenario with rapid and emission intensive economic growth, i.e. combining SSP 5 and RCP 8.5 and a second scenario with low-carbon and sustainable economic growth, i.e. combining SSP 1 and RCP 2.6. Whilst the average financial propagation of shocks amplifies risks by a factor of 2 for most countries, for the UK, the amplification ratio can reach a factor of 10 in a high-impact scenario without adaptation. The UK is therefore one of the most impacted countries internationally (and under one scenario, the most impacted country), due to coastal flood risks and its role as a global financial hub.

For banks, climate-related risk factors manifest themselves in increasing credit, market and operational risks (Source: PRA, 2018[cdxcviii]). Credit risks emerge if damages from physical risks are not insured, and the financial burden falls directly on companies, impairing asset values and reducing the value of investments held by financial institutions, including banks. Market risk refers to the risk of changes in the market price of sovereign debt for those countries most susceptible to the physical impacts of climate change. Sovereign bonds represent over 40% of the global bond market and are one of the most important asset classes held by investors globally (discussed in later section). Finally, operational risk refers to the risk of weather events impacting on business continuity, including branch networks, offices, infrastructure, processes, and staff (which is covered in the other risks in this chapter). In terms of transition risks, reputational risk could also arise from shifting sentiment among customers and increasing attention and scrutiny from other stakeholders on the banking sector's response to climate change (PRA, 2018).

In 2020, the Bank of England (2020) reported that there is clear evidence that banks, insurers, and the financial system will be impacted by physical climate change risks and the transition to a carbon-neutral economy. For example, just under 10% of the value of mortgage exposures in England is on properties in flood-risk zones (a domestic risk, i.e. from impacts of climate change in the UK) (BoE, 2020).

The total value of the assets at risk (from climate change) in the UK banking sector is not known yet. The Bank of England plans to assess the system-wide financial risks from climate change and explore whether climate-related factors should be included in a future Biennial Exploratory Scenario (BES), due in mid-2021.

However, a number of studies have used global economic Integrated Assessment Models (IAM) results to look at potential impacts on financial markets. These provide some global estimates which inform the UK context, though these are primarily international risks that affect the UK (i.e. ID8).

The Economist Intelligence Unit (2015[cdxcix]), using analysis by Dietz et al (2016[d]), looked at the 'expected value at risk' of global financial assets to climate change, where the value at risk measures the size of the loss a portfolio may experience, within a given time horizon, at a particular probability of occurrence, from climate change. The analysis used estimates using the DICE model, but looking at different future scenarios. It also used a wide definition of manageable assets, to cover all assets held by non-bank financial institutions, reporting these at US$143 trillion in 2013. The dividend approach was discounted from both the perspective of a private investor and a government.

The analysis estimated the value at risk, as a result of climate change, to the total global stock of manageable assets ($143 trillion) as $4.2 trillion (mean expected losses, discounted in present value terms, when using private sector discount rates [of 5.5%]), between now and the end of the century. This translates into climate change causing permanent, present value losses to current manageable assets of 3% on average ($4.2 Trillion). Much higher values were derived across the full climate uncertainty range, and when public discount rates were used. For example, it estimated that warming of 5°C would lead to US$7 trillion in losses, or 5% of global assets value —more than the total market capitalisation of the London Stock Exchange— while 6°C of warming is consistent with a present value loss of US$13.8 trillion to manageable financial assets, roughly 10% of their global total. The study reports that the asset management industry is particularly subject to tail risks: lower probability but higher impact losses.

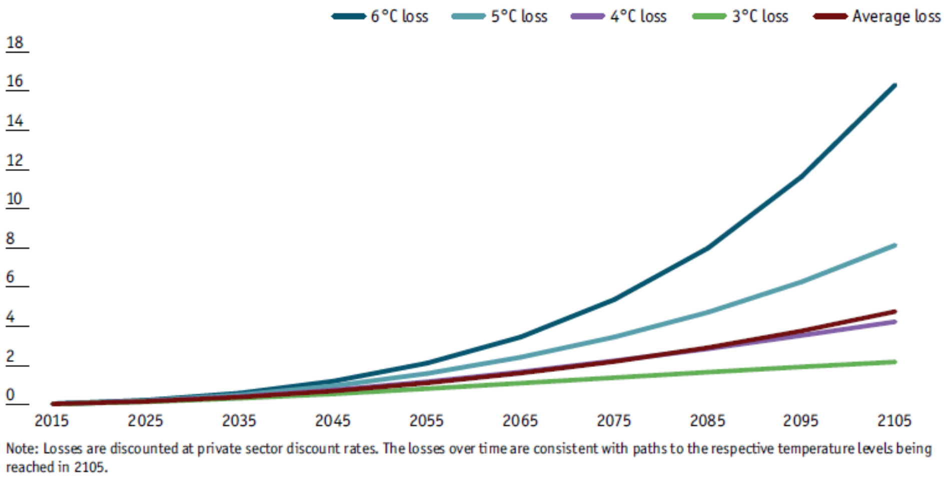

Figure 22 Present value loss to current manageable assets (trillion $, 2015 prices). Source EIU, 2015.

The EIU (2015) report also presents a complementary analysis, which uses estimates made using the DICE model of the impact of climate change on the stock of non-financial capital assets (a capital approach). The initial stock of non-financial assets in DICE was updated and was $207 trillion in 2015. Climate change affects the stock of non-financial assets in two ways: by lowering the rate of return and by directly destroying assets. Climate change was projected to, on average, reduce the capital stock in 2100 by 9%, and up to 28% at extreme outcomes. Overall, the EIU modelling suggests that much of the impact to manageable assets will come through lower asset returns, affecting the entire portfolio, rather than direct damage, which would be more localised. It is noted that these results are a function of the DICE model, and its coverage and functionality. While this includes non-market sectors and even low-likelihood high impact events, this model is partial, and recent updates of the model do produce higher damages (Nordhaus et al., 2017[di]).

The UK banking sector assets totalled $10.7 trillion (equivalent to £9 trillion) at the end of 2018, the fourth largest in the world and the largest in Europe. Around half of UK banks' assets are dominated in sterling, the remainder are foreign-currency based. Using the estimates of EIU (2015) mentioned above, 3% (average present value losses) to 28% (using the capital approach) losses in present value terms would equate for the UK to £270 billion to £2.52 trillion worth of losses. However, the majority of this exposure is assumed to be through international risks (i.e. ID8).

A further analysis of the impacts on financial markets was undertaken by Mercer (2015[dii]). This looked at both the physical risks but also opportunities. The analysis used the FUND integrated assessment model and adapted an existing investment model to allow model inputs for different scenarios, and to allow a climate sensitivity adjustment for different asset classes and industry sectors (i.e. the asset sensitivity to the TRIP factors). The results estimate the impact on return expectations between 2015 and 2050 when climate considerations are included. It found that climate change risks could impact investment returns. For a 2°C pathway, it reports that investors could see a negative impact on returns from developed market equity and private equity, especially in the most affected sectors. However, this scenario would be likely to lead to gains in infrastructure, emerging market equity, and low-carbon industry sectors. Under a 4°C pathway, chronic weather patterns pose risks to the performance of asset classes such as agriculture, timberland, real estate, and emerging market equities.

CISL (2015[diii]) reports that under more extreme climate scenarios, short-term shifts in market sentiment - from awareness of future climate risks - could lead to economic shocks and losses of up to 45 per cent in an equity investment portfolio value (and 23 per cent loss for fixed income portfolio), of which around half would be hedgeable and half not, the latter, meaning investors and asset owners are exposed unless some system-wide action is taken to address the risks.

These risks will involve portfolios of UK investments (and the risks for B4) and risks associated with international investments (ID8).

There are some risks where there could be sizeable UK exposure. One of these is real-estate portfolios, which seems to be a particularly high-risk area and one where there is greater appreciation of risk. In other countries this has started to affect investor confidence. US, for example, there is some evidence that properties exposed to potential sea level rise are selling at a discount relative to less exposed properties (Bernstein et al., 2018[div]) and in turn, this information is starting to be considered by real estate investors and funds (UNEPFI, 2019[dv]).

CISL (2019[dvi]) modelled the potential increase in physical risk from climate change to the interests of investors and lenders, especially those with interests in real estate and infrastructure assets. It was found that in the UK, under a 4°C warming scenario, in the 2050s UK residential mortgage portfolios might see an increase in Average Annual Loss (AAL) from floods of 130%, and the number of properties at considerable risk of flood (1.3% or 1 in 75 annual probability above) could increase by 40%[29].

There has been some analysis of the risks to funds in other European countries, that provide some information on the possible scale of risks to the UK financial sector. South Pole Group (2016[dvii]) investigated whether climate change could lead to risks in financial market stability, primarily looking at German equity funds, based on a literature review and analysis. This looked at physical and transition risk. The study concluded that physical risks represented a very low risk for financial market stability in Germany and Europe in the short term (by 2020) to medium term (in 2020-2030), i.e. it is very unlikely that the physical effects of climate change could cause a significant risk for the financial market stability. Transition risks were considerably more relevant.

Insurance risk

There are a number of issues related to insurance. The first is the role for insurance to act as a risk spreading mechanism, and thus help reduce the impact of current and future risks. Climate change will affect this model, and could affect insurance affordability for households and businesses. The second is the exposure to the insurance and re-insurance industry in the UK, i.e. the risks for the financial market in the form of higher and more volatile losses, both from impacts in the UK (B4) and from impacts internationally (ID8). Importantly, climate change could affect the insurance market by making some risks uninsurable and/or raise premiums beyond affordability for certain categories of businesses and households income groups. This could in turn reduce demand for insurance products and negatively affect insurance companies' profitability. Nevertheless, this could also prompt insurance companies to find innovative ways to reduce risks. The most obvious area for this in for flood insurance (though in theory, there are potential risks for other major hazards where there is an insurance market, i.e. windstorms, wild-fires, etc.).

Flood insurance coverage enhances the financial resilience of households to flood risks. However, climate change is projected to increase flooding in the UK, and thus to increase insurance premiums, potentially making insurance coverage unaffordable for low-income households. These higher premiums could reduce the demand for insurance coverage, and decrease the ability of insurance to provide financial protection against destructive floods. If insurers have to hold more capital to cover rising expected losses, this will also decrease the amount of money available for investment. However, insurers can adapt over time by increasing premiums markedly after an event. Insurance can be frequently re-priced and there are already examples of private insurance cover being withdrawn, negatively impacting property values.

There are several studies that have looked at these issues. Tesselaar et al., (2020[dviii]) looked at patterns of unaffordability - the percentage of the population in high-risk areas that cannot afford the

[29] These results stem from an analysis of seven large, relatively well geographically diversified mortgage portfolios and take account of coastal, fluvial and surface water flooding. It is an assessment of how much additional damage today's portfolios might face under the climatic conditions expected in the 2050s, assuming a continuation of trends in the recent past regarding community-based adaptation (CISL, 2019).

flood insurance premium - from increasing floods (taking account of each countries insurance model) for a high warming (RCP8.5) scenario across Europe. The study then looked at flood insurance penetration rates. While the UK is not the worst affected, there are still projected decreases.

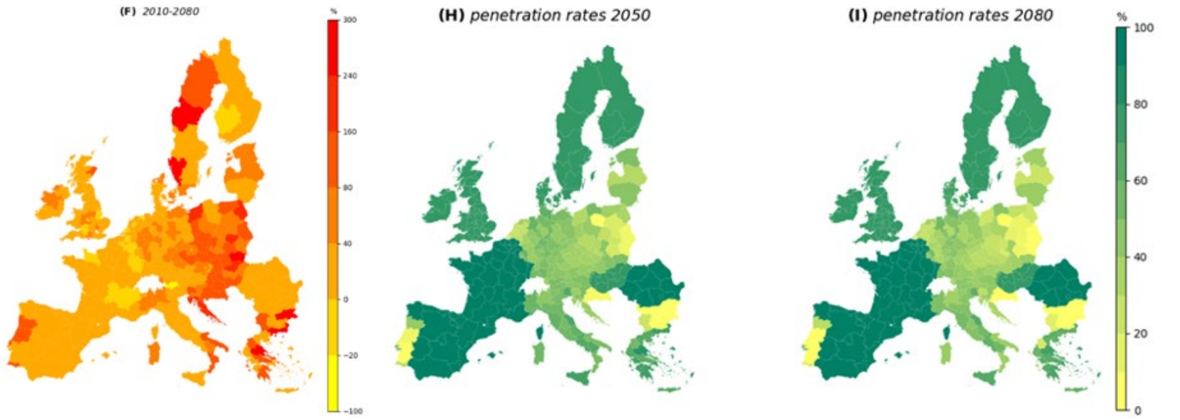

Figure 23 The percentage change in unaffordability under status-quo insurance arrangements for households in high-risk areas under RCP8.5-SSP5 (left) and flood insurance penetration rates under current insurance arrangements for households in high-risk areas under 2050 (middle) and 2080 (right).

De Nederlandsche Bank (2017[dix]) undertook a study on the Dutch financial sector, again, looking at physical climate risks and transition risks. For the former, this included the consequences of climate change for insurers, and the impact of large-scale flooding on the financial sector. The analysis found that climate change will put an upward pressure on insurance premiums, which could moreover lead to shock-induced price increases. There was also considered to be a risk from uninsured losses, notably those covered by Government - the financial sector may incur losses through their exposures to these parties. Looking internationally, the study found Dutch financial institutions appear to have only limited exposures in countries that are most vulnerable to climate change. These provide some potential lessons for the UK, though there is much more international exposure in the UK (as identified by Mandel et al., 2020[dx]).

Several UK banks have developed or are developing approaches to assess the financial risks of flooding on their mortgage books, and some are taking action to mitigate future risks (PRA, 2018). This, in combination with high penetration of private market insurance and the existence of Flood Re, makes the net current and short-term financial risk of flooding moderate (Surminski, 2016). However, the financial risks may increase as floods in the UK become more frequent and severe due to climate change. These financial risks could emerge if, for example, insurance firms are unable to pay out claims, Flood Re is discontinued, or insurance becomes unavailable (Surminski, 2016[dxi]).

While most focus has been on floods, windstorms are also potentially important. Initial ABI estimates for windstorm damage pay-outs from the 2020 storms Ciara and Dennis are £149 million, with 61,000 domestic property claims, totalling £77 million, 9,000 commercial property claims at £61 million, and 3,500 motor claims at £11 million (Insurance Journal, 2020). Robinson et al (2017[dxii]) looked at different RCPs and projected the changes in frequency and intensity of windstorms, looking at the average annual loss (AAL), i.e. annual insured loss aggregated over an entire year, the 1.0% exceedance probability (100-year) loss, and the 0.5% exceedance probability (200-year) loss. The results indicated a change in the overall AAL of 11%, 23%, and 25% for the 1.5 °C, 3.0 °C, and 4.5 °C cases, respectively (corresponding to RCP 4.5 at 2050-59, RCP 8.5 at 2070-79 and RCP 8.5 at 2090-2099). The analysis also indicated a possible increase of up to a 30% increase in the 100-year return level loss and up to 40% in the 200-year return period loss, though the distribution of these changes are not equal across the country. However, there is considerable uncertainty over future windstorms and other studies find little evidence that climate change will increase European windstorm losses[dxiii].

There are also the risks from international exposure (though these are captured in ID8).

Finance sector opportunities
Several reports highlight opportunities for the UK finance sector (K-Matrix, 2013[dxiv]; PwC, 2013[dxv]), such as increasing demand for new products such as weather-indexed crop insurance and catastrophe and green (resilience) bonds. These are covered in the opportunities in B7.

Overall effects
The analysis above highlights the potential scale of risks is potentially very large, although this is partly from physical climate risks that occur in the UK (relevant for this risk, B4) and partly from physical climate risks that occur overseas and impact back to the UK through financial markets (ID8). There are also some overlaps with other risks, e.g. the impacts of floods on property (residential and non-residential) is partly captured in the direct effects of these risks, even though these spill over to B4. The welfare effects of these risks relate to the loss of profits to UK companies, and/or the potential increases in the cost of financial products to consumers or the lack of their availability (e.g. for insurance), as well as the wider impacts to the UK in terms of the effects on the public finances. These have not been explicitly estimated to date, though the costs associated with the categories described above allow us to make judgements on the indicative values, presented in the table below.

Table 97 B4. Risks to finance, investment and insurance including access to capital for businesses. Note some potential overlap with ID8.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK		Very high	Very high	Very high	Very high	Very high
England		Very high	Very high	Very high	Very high	
Other DAs		Unknown	Unknown	Unknown	Unknown	
Confidence		Medium	Medium	Medium	Medium	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation
It is difficult to estimate the potential costs and benefits of adaptation for the diverse set of areas covered in this risk. There are already activities to increase climate related financial disclosures, in line with TCFD, which is likely to stimulate more consideration of adaptation, and the evidence in this areas will grow.

B5. Risks to business from reduced employee productivity due to infrastructure disruption and higher temperatures in working environments

There is a well-established literature of studies that consider heat-humidity-related climate change impacts on labour productivity (sometimes reported under occupational health). Earlier studies report that work output is affected by heat and humidity (Kjellstrom et al., 2009: Kjellstrom et al., 2014[dxvi]). In order to cope with heat, there is typically a reduction in work intensity or an increase in breaks. This occurs through self-pacing which reduces output, with the end result of lower employee output. These reductions in work intensity can translate through into labour productivity, which is a measure of output per employee or unit of labour[30]. In extreme heat, there are also risks of heat stress, heat exhaustion, heat stroke and even fatality. These effects apply to outdoor workers in particular, but also to indoor workers who are not working in a temperature-controlled environment, noting that there are occupational standards for workers.

[30] Labour productivity measures the volume of gross value added (GVA) produced per unit of labour input, with hours worked as the preferred labour input (NAO, 2020).

There are several studies that have applied these approaches to the UK. Kovats et al (2011[dxvii]) and Lloyd et al (2016[dxviii]) estimated the loss of productivity (days lost) from climate change at the national level across Europe, including for the UK. For the UK, the values were extremely small. This contrasts to other southern regions of southern Europe, where labour productivity losses were very high. For the UK, no labour time was projected to be lost in the 2030s and 2050s. Similarly, Ciscar et al. (2014[dxix]), using a CGE model, estimated that in southern Europe GDP labour productivity losses due to climate change are close to 1.3% of GDP, mainly due to agriculture impacts and decreased outdoor labour productivity by the 2050s. In the same study, for the UK, very little labour time was estimated to be lost in the 2030s and 2050s. More recently, Gosling et al., 2018[dxx], estimated outdoor labour productivity losses in the UK at 0 to 2% by the end of century, but effectively 0% in the near-term (no adaptation). It estimated indoor labour productivity losses in the UK would be 0%.

In practice, however, there are likely to be some labour productivity losses, at least during heat waves. Extreme weather events, such as heat waves, can impact productivity. As described in CCRA2 and outlined in the National Business Resilience Planning framework, severe weather can also impact indirectly, e.g. by causing transport disruption (Cabinet Office, 2014).

Some past events in the UK suggest extreme outdoor temperatures could have significant effects on production. The 2003 European heatwave is estimated to have resulted in a loss in manufacturing output in the UK of £400 to £500 million (2003 prices) (Martin et al., 2011[dxxi]).

Baglee et al. (2012) in CCRA1 attempted to quantify and monetise the impact of overheating on employee productivity in the UK by drawing on work by Capon and Oakley also in CCRA1 (2012[dxxii]) and data from the Inter-Departmental Business Register. Their analysis considered the number of days per year when the temperature exceeded a certain threshold by region. Using a 26°C (or 28°C) threshold, approximately five (or three) million staff days were lost in 2010, which is 0.1% (or 0.06%) of the staff time available. Based on an average staff cost of £150 per day (average wage, plus social costs) this resulted in a loss of £770million (or 460 million) in 2010. They projected the increase in hot days to the 2020s, 2050s and 2080s and estimated lost staff hours due to high internal building temperatures, the results of which suggested a potential doubling in lost productivity as an upper bound by 2020 (p90 values), with little change at the lower bound (p10 values). By the 2050s, the central estimate was for an average 3-fold increase, rising to an average increase of 8-9 times for the high emission, p90 case. This pattern continued into the 2080s, with roughly a 50% increase in lost productivity for the p10 case, and an increase of between 10-50 times for the high emissions, p90 case. At the upper bounds and using the 26°C threshold, Baglee et al. suggest that the cost of loss in productivity due to building temperature could increase from a baseline of £770 million in 2010 to between £850 million and £1.6 billion in the 2020s; between £1.1 billion and £5.3 billion in the 2050s and between £1.2 billion and £15.2 billion in the 2080s. Using a 28°C threshold, the values were typically half the values based on a 26°C threshold. However, the current authors consider this is likely to be an over-estimate, as it leads to much higher values than other literature, and is unlikely to take account of existing air conditioning in London and the South East in business premises.

Costa et al (2016[dxxiii]) assessed possible labour productivity impacts for city economies. They report that total losses to the London economy could range between 0.4% of Gross Value Added (GVA) in a warm year in the far future (2081-2100). These varied by sector, with 24% of losses concentrated in the financial sector, and 18% in the construction sector. The authors estimated that productivity losses for workers were just below EUR 2 billion when using ISO standard, reaching EUR 4 billion when using US standards[31]. Averted losses as a result of adaptation measures such as behaviour change, air conditioning and insulation were also quantified (-€114 million to over €2.3 billion). This shows that labour productivity losses are affected substantially by the standards used (and thus likely cooling levels).

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[31] The authors used the ISO standard as the recognised international benchmark for heat stress (Standard ISO 7243) which is based upon the wet bulb globe temperature index (WBGT). To test the robustness of results, they compared the ISO standards with the US standard provided by the National Institute for Occupational Safety and Health (NIOSH).

Recent econometric analysis in the EU-funded COACCH research project (Schleypen et al, 2019[dxxiv]) used spatial econometrics combined with sub-national and high-resolution data to estimate the impacts of changes in temperature and heatwaves on sectoral labour productivity. The results found gradual changes in temperature and extreme heat events have significant negative direct impacts of on both industrial and construction labour productivity. They report non-linear relationship between outdoor temperature and labour productivity in industry and construction sectors. Productivity decreases below and above thresholds, and thus depending on the baseline climate, further increases in temperature can result in a negative impact.

In the agricultural sector, future climate change was estimated to affect labour productivity for the EU by 2% under RCP2.6, 4.2% under RCP4.5, 5% under RCP6.0, and 6.3% under unmitigated climate change scenario of RCP8.5 by 2070. In the industrial sector, these impacts are expected to be 1.3% (RCP2.6), 2.5% (RCP4.5), 3% (RCP6.0), and 4.5% (RCP8.5), respectively. For the UK, productivity losses were estimated to be between 1% (RCP2.6) and 5% (RCP8.5) by 2070.

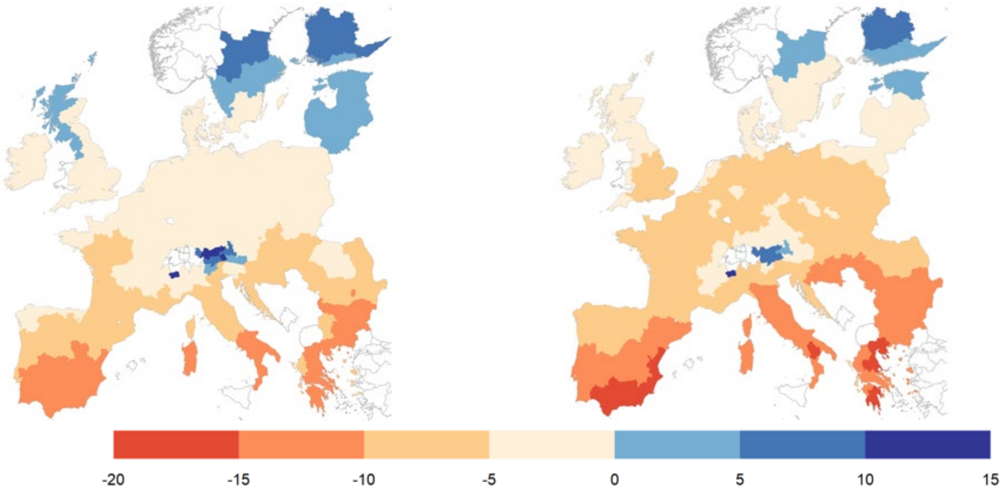

Figure 24 Future impact under RCP8.5 on industrial (left-panel) and construction productivity (right-panel) by 2070, compared to a reference period of 1985 - 2005.

These declines in labour productivity due to climate change will likely be transmitted through overall economic activity and have negative multiplier effects. Interestingly these results do show different results by DA, with Scotland projected to experience gains in industrial productivity, while the south east of England experiences the largest losses.

There is also an influence from other weather-related variables, notably rain, wind and snow, which affect productivity. These impacts are considerable in the UK, as evidenced in sectors such as construction. The influence of climate change on these is not well covered, but could add to heat extremes above.

However, the discussion above focuses on negative impacts, i.e. risks. Low temperatures are also associated with lower outdoor employee productivity and lower work output, and thus labour productivity. There is therefore the potential for benefits (opportunities) from higher winter related labour productivity with climate change, notably in some sectors.

The analysis above highlights that there is a wide range of results in the literature, and there is very little information that allows an analysis of the overall net effects, include the positive aspects as well as negative. However, some studies (notably Costa et al. 2016; and Schleypen et al, 2019) show that there are certainly potentially high (and plausibly even very high) risks to England, especially in London and the South East from higher temperatures, as the thresholds for labour productivity impacts are likely to be exceeded.

These risks can be mitigated by Business Continuity Management (BCM) plans, but the evidence is that the current level of uptake is low, particularly amongst small businesses, and uptake is generally reactive (e.g. occurring only after experiencing a climate event which resulted in losses). The Chartered Management Institute (CMI, 2013[dxxv]) found that just 31% of micro-organizations and less than half of small organizations (48%) utilise BCM plans, compared to 61% of medium and 74% of large organizations. BCM plans continue to be most prevalent in the public sector, with 73% of managers reporting BCM arrangements, and in large private sector organizations, with 70% uptake of BCM plans.

Table 98 B5. Risks to business from reduced employee productivity.

Valuation (Confidence in brackets)						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	Medium (High England, low other DA)	Medium (High England, low other DA)	Medium (High England, low other DA)	High (Very High England, low other DA)	
England	Medium	High (with range medium to very high)	High (with range medium to very high)	High (with range medium to very high)	Very high	Very high (high warming)
N. Ireland	Low	Low	Low	Low	Low	
Scotland	Low	Low (potentially positive)	Low (potentially positive)	Low (potentially positive)	Low (potentially positive)	
Wales	Low	Low	Low	Low	Medium	
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

There is some information on various adaptation options to reduce heat in commercial buildings. Day et al. (2019[dxxvi]) assessed 17 adaptation measures (drawn from a longer list of over 30), including both solutions for indoor and outdoor work, to address higher base temperatures as well short-term temperature peaks. The authors estimated the 'potential scale of impact' as well as the 'feasibility' of the measures. This also includes analysis of which actions can be taken forward by the private sector, by government and by individuals. The study also considers the economic costs of each adaptation measure including direct financial costs of implementing the measure, and a range of 'indirect' costs. Costa et al. (2016[dxxvii]) also estimated averted losses from alternative adaptation measures for three case study cities (Antwerp, Bilbao, and London) for a warm year at the end of the century (2081-2100). These studies identify a range of low and no-regret adaptation actions.

Some opportunities for labour productivity adaptation are identified such as transition to new ways of working (remote working, flexible working) and low carbon and energy efficiency buildings to maintain employee productivity (ILO, 2019[dxxviii], Day et al., 2019).

B6. Risks to business from disruption to supply chains and distribution networks

The CCRA3 Technical Report (Chapter 6) identifies that weather is already a significant cause of supply chain disruption, and this is projected to rise as climate hazards increase.

These effects include disruption that occurs in the UK – the focus of this risk – but also disruption that arises overseas, which affects businesses in the UK through supply chains (covered in the international theme, in risk ID1 and ID8). The economic valuation of these effects involves a number of elements, associated with different supply chains. It is also noted that some of the supply chain risks are captured in I1, on cascading risks, and I2, on flood risks for infrastructure (including transport), and thus some care is needed on avoiding double counting.

Supply chain disruption does have significant impacts on businesses already. The Technical Report (Chapter 6) reports on a LSE Business Survey that was undertaken specifically for CCRA3. The results that find that supply chain disruptions led to lost productivity as the most important consequences, but also that these events led to increased cost of working, and impaired service outcomes, as well as effects such as loss of revenues, delayed cash flow and reputational damage. The survey found that, on average, weather-related disruptions caused financial impacts between £12,000 - £250,000 over 2018/19 for respondents. While there is little evidence to relate the source of disruption to the consequences, adverse weather events tend to increase logistics costs (BCI, 2018). Other survey work highlights the costs of downtime. ITIC (2017[dxxix]) undertook a global study on 800 organisations (Reliability and Hourly Cost of Downtime Trends Survey) and report that nearly all organisations reported a single hour of downtime cost over $100,000 and one third over $1 million.

Similarly, a study by Allianz Global Corporate & Specialty (2012[dxxx]) estimated that 70% of damages by extreme weather events are linked to supply chain and procurement risks, such as disruptions and delays in delivery.

The Business Continuity Institute (BCI) published their latest Supply Chain Resilience Report (2019[dxxxi]) based on a survey to 352 respondents representing 15 sectors across 65 countries. 67% of respondent organizations reported having experienced one or more supply chain disruptions in the previous 12 months. The average cumulative cost of supply chain disruptions experienced by organizations in the previous 12 months was €10.5 million (this is calculated using the grouped mean), with 54% of respondents reporting cumulative losses of under €50,000 but a significant proportion (13%) reporting losses over €1m, with 1% reporting losses between €251-500 million and 1% above €500 million. The five main causes of disruptions were: unplanned IT/telecoms outage (44%), adverse weather (35%), cyber attack/data breach (26%), loss of talent/skills (21%), and transport network disruption (16%). The findings also revealed that although organizations are getting better at managing direct suppliers, they were finding it increasingly difficult to tackle tier 2 and tier 3 risks.

An early study by PWC (2008[dxxxii]) determined that 60% of companies affected by production disruptions show a reduction in turnover and rate of return in the following year, and the average return on assets declined by 5% and return on sales by 4%. PWC (2013[dxxxiii]) conducted an analysis – based on expert opinion– which provides an indicative analysis of domestic climate change threats and opportunities. They concluded that in the short-term (to the 2020s) extreme weather events, exacerbated by climate change, would increase volatility of prices and cause disruptions of supply. Over the longer term (to 2050s and 2080s) they conclude increasing impacts of average climate change and extremes could lead to more pervasive systemic changes to trade in food and other physical commodities.

The most apparent risk arising in the UK (as compared to internationally) are from impacts on UK suppliers, and from disruption to transport and logistics. This can include disruption to the transportation of raw materials, labour, capital or finished goods and services.

Supply chains rely upon a functioning and resilient infrastructure network, particularly ICT and transport. On road freight, DfT (2019[dxxxiv]) reports that in 2018 for GB-registered HGVs operating in the UK, there were 1.41 billion tonnes of goods lifted (1% higher than previous year), 152 billion tonnes kilometres of goods moved and 18.7 billion vehicle kilometres travelled. Freight is also moved by rail. In 2018/19, 17.4 billion tonne kilometres of freight were moved by rail. In 2018, all ports handled 483.3 million tonnes, with the EU remaining the largest trade partner: 81% of all port freight was international. In 2018, UK airports that received commercial air traffic handled 2.63 million tonnes of freight (freight set down and picked up at an airport), making air travel the least used mode for freight transport. Climate change is expected to impact on road, rail, sea, and air freight transport. Flooding and landslides can cause disruption to the road and rail network, and extreme heat can be an issue (see infrastructure section). For example, between 2006 and 2014 in England, 11% of road disruptions were attributed to weather-related incidents; and so were 24% of rail disruptions (CCC, 2014[dxxxv]). High tides and stormy seas can disrupt port and maritime services. Wind and storms can cause disruption to air travel, including air freight. The risks to the transport network were discussed in the infrastructure section, but the impacts of these risks affect business supply chains. While motorways and trunk A roads are usually relatively robust to withstand weather events and climate extremes (CCC, 2015[dxxxvi]), secondary (B and C roads) can experience issues especially in relation to drainage and erosion. This results from differences in pavement design, characteristics, age and maintenance regimes between secondary roads and motorways.

There is some information on the potential impacts of extremes on UK transport. Assuming no population growth and a continuation of current levels of adaptation, the length of railway line located in areas exposed to flooding more frequently than 1:75 years (on average) was projected to increase by 53% and 160% in the 2080s for a 2 and 4°C scenario, while the length of major roads affected increased by 41 and 120% (Sayers et al. 2017). These events will lead to supply chain disruption, with travel time delays, and knock-on effects on businesses as described above. However, there is currently not good evidence on how large these are in economic terms (see discussion in I2 on disruption to transport infrastructure and services).

There have been some studies of supply chain and procurement risks, focusing on disruptions and delays in delivery and transport due to extremes. Lühr et al. 2014[dxxxvii] review the literature on disruptions of production. They report estimates that 70% of damages by extreme weather events are linked to supply chain and procurement risks (such as disruptions and delays in delivery) with the remaining 30 % of damages due to direct physical damages of the production sites. They also cite other studies that find that 60% of companies affected by production disruptions show a reduction in turnover (of around 5%) and return on sales (of 4%) in the following year.

There has been some analysis on food supply chains and climate change (Watkiss et al., 2019[dxxxviii]) though these tend to focus on international linkages, and are covered in ID1. The impacts of climate change on food production in the UK are covered in the natural environment chapter (NE6).

However, national food supply chains do have high dependencies on infrastructure, in the form of water, energy, communication, and transportation. Disruption to any part of any of these systems can cascade through to other parts of the supply chain and is likely to have unexpected consequences (see discussion in infrastructure chapter). Briggs et al. (2019[dxxxix]) report that initial research, covering over 40 companies in the UK food supply chain sector highlighted that infrastructure was a key component within a supply chain. Current climate risks for the food supply chain primarily arise from extreme events and these risks are generally managed in the short term by rationing through price or quantity and in the long term by supply diversification and switching sources of supply (UK Foresight, 2011[dxl]). There are also potential risks from climate change affecting facilities, buildings, equipment and products involved in the food production process.

In conclusion, this review reveals no quantitative valuation of the impacts of climate change on supply chains in the UK, though lots of qualitative evidence to suggest this is an important risk. This is difficult due to the high interconnection and interdependency between different infrastructure upon which supply chains rely – nationally and internationally - and between trade businesses partners.

Table 99 B6. Risks to business from disruption to supply chains and distribution networks – domestic elements only (international elements in ID1 and ID7).

Valuation (Confidence in brackets)						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Medium	Unknown but possibly Medium - High	Unknown but possibly Medium - High	Unknown but possibly Medium - High	Unknown but possibly Medium - High	Unknown but possibly Medium - High
Confidence	Low	Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

<u>Adaptation</u>

There are some aspects of climate change risks and responses that have been quantified for food supply chain resilience. Even here, however, there is little information on the associated costs and benefits (in aggregate), as identified by recent review of food supply chains and adaptation (Watkiss et al., 2019[dxli]), though it did identify potential adaptation measures and their potential (qualitative) benefits and costs, indicating net beneficial further actions exist.

B7. Opportunities for businesses from changes in demand for goods and services

The CCRA3 Technical Report (Chapter 6) highlights that climate change will affect the production costs, comparative advantage, and demand for certain goods and services. This could lead to benefits for the UK, if sufficient information and climate change expertise is available, as businesses respond to market signals and exploit opportunities as they arise. It reported that the evidence base is constrained to a few areas, notably changing conditions for food and drink production, but also identifies a significant change in the growing prominence of climate advisory services. It reports that businesses that anticipate changing markets may be able to gain an advantage.

The valuation analysis has developed the analysis further, looking at the economic opportunities in a number of key areas.

<u>Tourism</u>

There is a reasonably good evidence base on the potential benefits to the UK from changes in beach tourism. These arise from the improved climate in the UK in the future, usually represented by an improved tourism comfort index (TCI), as well as the reduced tourism attractiveness of European summer destinations (notably in the Mediterranean). This leads to a greater flow of domestic and international tourism to the UK, captured through increased tourism expenditures in the UK.

There have been a series of studies that have looked at the potential economic benefits to the UK. Early work was undertaken in the UK climate impacts programme and cross regional studies (Hamilton, Tol and Hunt, in Metroeconomica, 2006), and there was an analysis in CCRA1. Taylor and Arigoni Ortez (2010[dxlii]) developed panel data models to explore the effect of climate variables on domestic tourism and apply these results to the hot summer of 2003 to estimate the beneficial effect the heatwave had on tourism in the UK. The model was used to estimate the impact of the hot weather of summer 2003 on domestic tourism in the UK, finding a positive impact on revenues ranging between £14.79 million and £30.32 million (of which £11.48 million and £23.54 million were for England).

Amelung and Moreno (2012[dxliii]) estimated the cost of climate change on tourism in Europe. They identify large differences in results depending on whether future socio-economic change (i.e. rising demand) is taken into account, but identify a strong redistribution of summer tourism away from

Southern Europe. Based on analysis of TCI, they project that the Southern UK could develop good conditions for summer tourism.

The PESETA II study (Ciscar et al., 2014) estimated the costs of climate change on tourism (the fall in revenues) at €15 billion/year for Europe by the end of the century (A1B). A further analysis in this study (Barrios and Ibañez Rivas, 2013[dxliv]) used a travel cost approach and hedonic valuation of recreational demand and amenities also in the long-term (2100). They estimated that in Southern EU Mediterranean countries, climate change would lower tourism revenues between -0.45% and -0.31% of GDP per year. In contrast, they estimated that in Northern European regions and the British Isles, tourism activity could lead to benefits, with the British Isles gaining + 0.3% of GDP per year respectively. However, the impacts depend on whether holiday duration and timing are fixed, or whether there is a redistribution to shoulder seasons (for visits to Mediterranean countries). If these adaptations occur, the gains to the UK fall, to 0.2% of GDP, i.e. gains are negated if tourists change duration and timing.

Perrels et al, (2015[dxlv]) also assessed regional tourism revenues from beach summer tourism in Europe by mid-century finding similar patterns to the studies above. They also investigated supply-side adaptation and conclude that warmer regions will see a shift to shoulder seasons, while cooler regions will shift towards the peak season.

These studies indicate a sizeable economic benefit by the 2050s for the UK. However, some types of tourism or tourism in specific areas could be negatively affected by climate change, for example in locations where sea levels rise and erode beaches, and also the Scottish winter sports tourism.

Agricultural production

The potential risks and opportunities for agricultural production were discussed in the natural environment chapter. In summary, while there are potential impacts to UK agriculture, there are also benefits. However, the analysis also identified potential opportunities, discussed in Opportunity NE9.

This reports that there are some specific opportunities from a changing climate, as warmer temperatures could improve the suitability for some agricultural production. As a concrete example, a case study on English wine by Watkiss et al (2019[dxlvi]) found climate change could lead to a positive shift to a more favourable (warmer) climate for grape growing, and this would lead to a major increase in production by 2040, which would generate revenues of potentially several £hundred million / year.

The analysis also identifies (NE6) that climate change may lead to opportunities for the UK, relative to international competitors. There are studies that indicate a growing comparative advantage for the UK for a number of agricultural products. This is partly because of the improved average climate in the UK, but also because of the change in comparative advantage, due to more negative impacts in Europe and internationally. These results highlight the difference when considering only domestic yield changes versus international trade, i.e. when using partial and general equilibrium models, rather than just crop models. Many recent studies (e.g. COACCH, 2019[dxlvii]) indicate potentially large benefits for UK agriculture, though it is stressed that the uncertainty ranges around any estimates are very large.

Adaptation goods and services

There is a potential opportunity for UK businesses, both domestically and internationally for adaptation goods and services, though most of the literature is more focused on the opportunities from the low carbon economy (e.g. REE, 2017). K-Matrix for BIS (2012[dxlviii]) provides a list of categories for the adaptation and resilience sector, which includes: architectural, climate change management, construction and retrofit, environmental finance, finance investment and insurance, risk management and business continuity, sustainable drainage and water management, transport infrastructure and water irrigation.

At the global level, CDP (2019[dxlix]) reported the cumulative opportunities for 225 companies at US$236billion in revenue from the provision of adaptation goods and services. In the UK, Surminski et al (2016[dl]) in CCRA2 presented data suggesting sales of adaptation goods and services by UK companies in 2011/12 were £2.1 billion, reporting this made the UK the seventh largest producer of adaptation goods and services globally, of which £0.3 billion were exports. Based on the best of the limited data available, global sales of adaptation goods and services were estimated to be £69 billion in 2011/12. There has been more recent analysis on the market for adaptation goods and services (sometimes called the adaptation economy) with a number of studies including REE (2017[dli]), KMatrix (2016[dlii], updated 2020[dliii]), Acclimatise (2016[dliv]) and Bonaventura (2018[dlv]). These identify opportunities for particular adaptation goods and services, especially in climate modelling, professional services including architecture and engineering, and finance and insurance products.

These indicate very large opportunities, although some care must be taken in considering these estimates, as the definitions of adaptation goods and services are not well defined in these studies, i.e. many numbers reported are forms of existing activities associated with managing the current climate, rather than planned adaptation. Further, much of the funding will be associated with delivering adaptation to address risks identified elsewhere in CCRA3, i.e. public procurement of large infrastructure investment for flood resilience that is delivered through private service providers. This means the values cited in the studies above need to be carefully considered to identify the additional benefits, e.g. the international export of adaptation goods and services with greater additionality.

Insurance and finance
While there are potential risks (see B4) there are also opportunities for the insurance and finance sectors. These risks include domestic and international opportunities, that will accrue to UK companies.

There is a large international insurance and reinsurance market based in London. Climate change is likely to reinforce the need for insurance, which could increase both domestic and international insurance, though as highlighted in B4, there are some potential risks. Expansion of insurance from UK companies into emerging markets could increase the global market share of UK adaptation insurance products and services. The magnitude of this opportunity is difficult to quantify, but opportunities could be 'very high'. A caveat is that over the longer term these opportunities may evolve into threats to insurers if products are not priced correctly, or if some events become uninsurable.

Similarly, London is a global centre for financial services and has been active in the green bonds market. Green bonds represent a new tool to mobilize resources from domestic and international capital markets to fund projects that meet certain criteria. Proceeds of green bonds are applied entirely for green activities that promote climate change mitigation, adaptation or other environmentally sustainable purposes. The market for Green bonds is high and growing, reported at $260 billion in 2019 (CBI, 2019[dlvi]) and will increase rapidly with the net zero transition, but this market is dominated on mitigation, accounting about 95% of current green bond funding (Tuhkanen, 2020[dlvii]). This is because mitigation projects offer financial returns, i.e. by investing in areas which generate reliable income stream for repayment such as renewables. Investment in adaptation and resilience of the natural environment for example are more public good in nature and typically do not generate returns in the form of income streams.

Of more relevance are resilience bonds and catastrophe bonds. There are a number of emerging products here. These include standard debt instrument to raise finance for investing in resilience. The first major resilience bond ($700 Million) was recently launched by the EBRD[dlviii] and there is an opportunity for the UK to use international expertise, risk modelling firms, specialist credit ratings, accounting teams and financial regulators. There are also more complex resilience bonds (Vaijhala et al., 2018[dlix]), which are a variant of catastrophe bonds, designed to help manage the financial risk from catastrophes, while simultaneously promoting investment in infrastructure that mitigates physical risk. Catastrophe (Cat) bonds are a type of insurance-linked security and provide protection equivalent to an insurance policy. Cat bonds enable sponsors to transfer catastrophe risk to capital market investors.

The overall market for adaptation green bonds or resilience bonds, is not currently known. However, total adaptation financing needs in MIC and LDCs are very large, estimated at $240 – 300 Bn per year by 2030 (UNEP, 2018[dlx]), as compared to global current public adaptation finance flows (international and domestic) which are around $30 Billion/year (CPI, 2019[dlxi]). This implies there will be a need for additional adaptation financing internationally. The UK has expertise in in Green bonds and financing (and thus resilience bonds), which includes the surrounding 'ecosystem' that will be important for meeting climate bond and resilience bond standards[32]. It also has a strong comparative advantage in technical assistance for risk reduction (resilience) design, i.e. engineering consultancies.

Summary
Given the discussion above, we conclude the overall level of opportunities are potentially very high.

Table 100 B7. Opportunities for businesses from changes in demand for goods and services.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK		+Very High	+Very High	+Very High	+Very High	
England		+Very High	+Very High	+Very High	+Very High	
N. Ireland		Unknown	Unknown	Unknown	Unknown	
Scotland		Unknown	Unknown	Unknown	Unknown	
Wales		Unknown	Unknown	Unknown	Unknown	
Confidence		Low	Low	Low	Low	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation
Given the range of sectors and opportunities it is difficult to identify specific costs and benefits of adaptation. There are sectors where analysis has been undertaken (e.g. Watkiss et al., 2019 for wine) which indicates that under a scenario where wine growers were able to realise the benefits of climate change due to better information (and appropriate response), and at the same time introduce adaptation measures to address potential variability risks, there would be very large economic benefits, and a high benefit to cost ratio.

Summary and Discussion of Business Theme

The overall summary of the results is presented below. The business and industry theme is the one theme where the evidence has changed most significantly since the CCRA1 valuation and there is much more evidence available. This is due in large part to the greater interest in climate-related financial disclosures for physical climate risk, as advanced by the Task Force on Climate-related Financial Disclosures, the Network for Greening the Financial System, and the Bank of England. However, there are still relatively few studies of the economic costs of climate change. The analysis indicates that this is an area where there are potentially very large economic costs, but also potentially very large economic benefits.

One of the largest risks for this theme (very high, £billions/year) is from flooding (river and surface) (B1) from the direct and indirect risks involved, the latter including business disruption (captured in B6). There are also potentially very large risks from climate change to the UK finance, investment and insurance sectors (i.e. to financial services and markets). These involve risks that arise in the UK, but also risks that arise internationally that affect UK businesses and investments (captured in ID8).

[32] Climate Bonds Initiative convened an Adaptation and Resilience Expert Group (AREG) to design a set of principles for defining climate resilience assets and bonds, and to guide the integration of criteria for climate adaptation and resilience into the Climate Bonds Standard.

While it is often difficult to disentangle domestic risks, they are considered to be potentially very high, i.e. equivalent to £billions/year, not least because of issues with rising climate extremes and insurance.

Similarly, there are potentially high risks from disruption to supply chains and distribution, but it is difficult to separate the evidence into the risks that arise in the UK (domestically), and the risks that arise internationally (captured in ID1 and ID7 in the International Chapter). These risks also include elements captured in other risks, e.g. for flooding of sites (B1) and transport disruption (I2).

There is also an important risk around labour productivity (B5), though the individual and overall aggregate effects are more uncertain. The UK currently does not have an optimal climate for outdoor work, and there are some important potential benefits for some sectors under future climates. These might be particularly important for Scotland. At the same time, there are potentially large (negative) impacts from heat related effects in the south of England, especially associated with extreme temperatures. These will affect outdoor work, but also indoor productivity, though the latter could occur as either an increase in cooling demand in buildings (given occupational standards) or a decrease in productivity. Either could be very significant in economic terms, especially later in the century (see also H6).

Finally, there are also considered to be large potential benefits (opportunities). Some of these arise from changing conditions in the UK (e.g. the improved suitability for wine growing), some from the comparative advantage gained as other regions internationally suffer potentially greater negative impacts (e.g. Mediterranean summer tourism) and some from the opportunities for new goods or services (in the UK and internationally) that UK businesses could provide (e.g. new insurance products).

Table 101 Summary of Risks and Opportunities for the Business and Industry Theme.

Risk/Opportunity	Present Day	2050s, on a to pathway stabilising at 2°C by 2100*	2050s, on a pathway to 4°C at end of the century#	2080s, on a to pathway stabilising at 2°C by 2100*	2080s, for 4°C world at the end of the century#	Confidence
B1. Risks to business from flooding	Very high	Very high	Very high	Very high	Very high	High
B2. Risks to business and infrastructure from coastal change	Medium	Medium	Medium	Medium	Medium	Low
B3. Risks to businesses from water scarcity	Medium (England only)	High (England only)	High (England only)	High (England only)	High (England only)	Low
B4. Risks to finance, investment and insurance		Very high (England only, other DA unknown)	Very high (England only, other DA unknown)	Very high (England only, other DA unknown)	Very high (England only, other DA unknown)	Low
B5. Risks to business from reduced employee productivity	Low	Medium (High England, low other DA)	Medium (High England, low other DA)	Medium (High England, low other DA)	High (Very High England, low other DA)	Low
B6. Risks to business from disruption to supply chains and distribution	Medium	Unknown but possibly Medium - High	Unknown but possibly Medium - High	Unknown but possibly Medium - High	Unknown but possibly Medium - High	Low
B7. Opportunities for businesses from changes in demand for goods and services		+Very High (England, other DA unknown)	+Very High (England, other DA unknown)	+Very High (England, other DA unknown)	+Very High (England, other DA unknown)	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year.

International Dimensions

The list of risks and opportunities considered in CCRA3 Technical Report for international dimensions are shown below:

Table 102 CCRA3. Risks and Opportunity for the International Theme.

Risk/Opportunity
ID1: Risks to UK food availability, safety, and quality from climate change overseas
ID2: Opportunities for UK food availability and exports from climate impacts overseas
ID3: Risks to the UK from climate-related international human mobility
ID4: Risks to the UK from international violent conflict resulting from climate change overseas
ID5: Risks to international law and governance from climate change that will impact the UK
ID6: Opportunities from climate change (including artic ice melt) on international trade routes
ID7: Risks associated with international trade routes
ID8: Risk to the UK finance sector from climate change overseas
ID9: Risk to UK public health from climate change overseas
ID10: Risk multiplication from the interactions and cascades of named risks across systems and geographies

The quantitative evidence base international risks and opportunities is generally lower than for the domestic themes covered in previous chapters, and this makes it more difficult to provide estimates of monetary valuation. For this reason, many of the estimates in this chapter are based on expert judgement. There is also less information on how these international risks might affect the DAs differently, and therefore only UK values are reported, though where we identify potential DA differences, these are highlighted.

It is noted that previous studies (e.g. Foresight, 2011[dlxii]) have hypothesized that the potential size of international climate effects on the UK could be of the same order of magnitude, or possibly greater, than those that arise domestically. The relative balance of international versus domestic risks is considered at the end of this chapter.

ID1: Risks to UK food availability, safety, and quality from climate change overseas

Climate change has the potential to lead to major effects in the agriculture sector internationally, including changes to production, with potentially risks (e.g. from lower rainfall or increasing variability) but also potentially positive effects and thus opportunities (e.g. from CO_2 fertilization, or extended growing seasons) (IPCC, Porter et al., 2014[dlxiii]). These can arise from changes in mean weather variables, as well as changes in the risks of extreme events. They can also arise from indirect effects, notably shifts in the range and prevalence of pests and disease. These changes will lead, in turn, to effects on aggregate production, supply chains, prices and trade, and even possible risks to food security and the breakdown of food systems (Porter et al., 2014). Chapter 7 of the CCRA Technical Report summarised the evidence on this risk. It reported that climate change is likely to exacerbate disruptive events that impact on agricultural production and food supply chains (droughts, agricultural pests and diseases, storms), with increased risk of disruptions associated with multiple production areas, and the potential increase of risk cascades amplifying these effects. This is important because the UK is not self-sufficient in food production, and there is a strong reliance on international markets (which in turn affect consumer prices).

For the analysis in this report, additional evidence has been identified, especially from the economics literature. This is important, because most of the available literature is characterised in terms of yield reductions. To understand the full effects of international changes in agriculture, it is important to consider the economic system, including trade and prices. This means a focus on how international effects can lead to potential impacts in the UK, which is predominantly associated with the change in consumer surplus as a result of changes in food prices.

The main issue with such an analysis is that the effects of climate change on agriculture internationally is very uncertain, and there is an extremely wide range of outcomes reported in the literature, from modest gains to dramatic losses. The effects vary according to the methods used but also a number of critical assumptions along the pathway of analysis from biophysical effects to economic analysis (Watkiss and Hunt, 2018[dlxiv]: COACCH, 2018[dlxv]) and include:

- The boundary of the study, whether UK, European or global;
- The future emission scenarios and climate model projections considered;
- The type of impact analysis undertaken – with different results noted for crop models versus econometric analysis - and if extreme events as well as average climatic shifts are considered;
- The inclusion or exclusion of the positive effects of CO_2 fertilisation;
- Consideration of additional indirect effects, such as pests and diseases;
- The type of economic analysis and whether this uses partial or general equilibrium modelling, and importantly assumptions about trade (related back to the study boundary);
- Transport modalities and their vulnerabilities to climate change risks;
- Patterns of socio-economic development that exacerbate the climate risks likely to disrupt production and transport of food;
- The assumptions about reactive adaptation, whether farm-level (local) or at the macro-level (e.g. comparative advantage, trade, price effects).
- The cross-sectoral issues that may exist that constrain adaptation, e.g. competition for water or land, including the synergies and conflict with low carbon trajectories.

Therefore, while the literature (e.g. IPCC, 2014) reports that global food production is projected to decrease with increasing global mean temperature, this is primarily a conclusion based on yield changes. The consideration of the same risk from an economic perspective is likely to focus on different metrics and can lead to different results, as farmers and/or markets adjust, e.g. as changes in prices in some places incentivise additional land into production to meet demand.

The starting point is to examine the current effects of weather-related impacts on international agriculture on the UK.

The UK imports a high proportion of food – in fact almost half of food consumed (in the UK), and the trade deficit in food, feed and drink in 2019 was £24.3 billion (Defra, 2020[dlxvi]). The UK imports food from over 180 countries. This means that relatively small changes in prices internationally, when basic food commodities are predominantly sourced from a region impacted by a specific climate risk(s), could have a large overall economic impact – as food and non-alcoholic drink comprise around 11% of household expenditure.

To date, the UK Government has considered that UK food supply is relatively resilient to supply interruptions occurring in specific countries as well as to disruption to domestic UK production (i.e. supply is sufficiently diversified and risk is spread) (Defra, 2017; Defra, 2018[dlxvii]). Retailers and large food service operators have -in the past- been able to switch sources of supply rapidly if required, as demonstrated during a range of crises including severe weather, transport disruption and Industrial Action (Defra, 2018[dlxviii]). However, high import dependency can increase risks. For example, a spell of unusually cold and stormy weather in Southern Spain in January/February 2017 resulted in there being both physical rationing and a trebling of purchases and prices of iceberg lettuces and broccoli in English supermarkets.

Furthermore, there is evidence that current international food shocks can cascade through to price increases in the UK, increasing the consumer price of food. Ray et al. (2015[dlxix]) estimated that, globally, for substantial areas of the global breadbaskets, current climate variability accounts for roughly a third of the observed yield variability.

A study for JRF (2016[dlxx]) explored the link between food price shocks and UK household expenditures, as reflected by changes in UK food prices. This found that recent historical patterns of high cereal prices associated with extreme weather events in major world production regions (the food price spikes in 2007/8 and 2010/11) were transmitted through to the UK and were reflected both in individual food products, such as bread, cereals and biscuits & cakes that rely directly on cereals, as well as meat and dairy where cereals are used as an input for livestock. Both of these spikes can be attributed, in part, to extreme weather events, and both increased prices internationally by around 40%, though there were a series of other factors that were involved. The JRF analysis found that whilst food prices rose at the same rate as overall consumer prices between 2001 and 2007, the increase in food prices between 2007 and 2011 was twice as high (26% compared to 14%). For example, the food bill for an average family rose and was 12% more in 2011 (although low-income households responded by buying less food). This suggests, implicitly, albeit weakly, that a global price – UK consumer price relationship may exist. It also suggests that these effects can be large in economic terms, although these price spikes are currently infrequent. Since the food price increases noted above imply a cost of up to £5 billion, adopting a "what if" assumption of a frequency of 1 in 20 years implies an annual welfare cost of £250 million. We adopt a tentative ranking of "High" in the current period, in the first instance – the uncertainty in this ranking reflecting the lack of knowledge we have on the current and likely future frequency of this type of food shock and price spike.

Moving to the effect of future climate change, this will affect the productivity of food production internationally, directly and through a wide range of factors. These could include (UK Food security Assessment, 2010; Porter et al., 2014[dlxxi]; GSF, 2012; 2018[dlxxii]):

- Changes in production of primary food produce, both from changes in agro-climatic shifts, but also from changes in the patterns of extremes. These effects may also arise from changes in pest and disease prevalence and range, impacts on food manufacturing, etc.
- Negative impacts on food prices from effects on production in domestic and global food markets.
- Damage to facilities, buildings, equipment and products involved in the food production process, including loss of water and power for production (overseas, and in the UK);
- Disruption to the transportation of raw materials, labour, capital or finished goods and services associated with the food supply chain.

The risks from climate change are most likely to manifest themselves in the price levels of food products rather than their physical availability Climate change is likely to result in greater price volatility with associated costs both for the consumer (in periods of higher prices) and producer (where prices are uncertain leading to less investment in agricultural productivity), For some food types, UK consumers have the option of substituting to alternatives; for others, this will imply increasing expenditure which will affect poorer households disproportionately (JRF, 2016). While there are market mechanisms currently in place to mitigate the effects of food price hikes and volatility, the short-term economic and social costs from climate related disruption could be significant. Over time, price volatility will increase UK consumers' spending on food in both absolute and relative terms (PwC, 2013). However, the analysis of these effects in monetary terms is made difficult because of the uncertainty highlighted above.

Porter et al., (2014) synthesise the crop model literature at the global level, reporting that climate change impacts are likely to be modest for 2°C of warming, but increasing above these levels, with major negative impacts in 4°C scenarios. However, there is a very large reported range in the literature. Moreover, different results arise when these results are considered in economic models. This can be seen with the Agricultural Model Inter-comparison and Improvement Project – AGMIP, and results reported in Nelson et. al. (2013[dlxxiii]). This study compared the outputs of seven economic models – three economy-wide (general equilibrium) models and four agricultural market-specific (partial equilibrium) models – for harmonised climate scenarios, sampling five different crop models and two general circulation models. They report that climate change could lead to a 20% (mean) food price rise in 2050 globally, but with a large range from 0% to 60% (across the models). Yield losses and price impacts rise more sharply in later years under higher warming scenarios. It is stressed that this wide range emerges for one future scenario (and only two climate models) – the range would be larger when different futures and models are considered.

These results allow some indication of the possible magnitude to be assessed. This can take the current linkages on increasing international prices and the rise in UK food prices as seen in recent international price shocks, and use the results from the Nelson et al. study (the implied 20% (central) price rise in global prices under climate change). Such an analysis was undertaken in the JRF study (see above) and this found that such increases would increase the food bill for an average family by 9% by the 2050s (with a range of 0%-28%, reflecting impact range) assuming all other things being equal. This would be equivalent to a cost of £275/household/year (with a range of 0 to -£856). When applied to the number of UK households, this implies a potentially very high impact (i.e. billions/year).

However, there is high uncertainty around these estimates, reflecting the earlier discussion and the influence of different modelling approaches or assumptions. As an example, Balkovic et al. (2015[dlxxiv]) estimated the difference in welfare (the sum of producer and consumer surplus) with and without climate-induced yield shocks using the partial-equilibrium model GLOBIOM for a 2°C scenario (mid-century). They found that without adaptation, Europe experienced a loss of USD 1.96 to 6.95 billion/year, but when adaptation was included, climate change had an overall positive monetary aggregated impact of USD +0.56 billion/year. Macro-economic modelling results also tend to report more positive effects, due to market driven (autonomous) adaptation, e.g. Szewczyk et al (2016[dlxxv]) looking at the global level, found that market-based adaptation reduced climate change damages by approximately a third (compared to a case without adaptation) for both GDP and welfare. It is therefore appropriate to note the range of uncertainty with this risk.

It is noted that there also risks along food supply chains (which overlaps with B6). For example, Allianz Global Corporate & Specialty (2012[dlxxvi]) estimates that 70% of damages by extreme weather events are linked to supply chain and procurement risks, such as disruptions and delays in delivery. However, delays in transportation chains are only likely to lead to very short-term disruption.

Finally, there is some potential for large-scale effects from climate tipping points, i.e. affecting major international production areas (GFSP, 2017[dlxxvii]). This most obviously relates to the production of food that predominantly emanate from a region significantly impacted by climate change. An example is that of rice production in South Asia. These could significantly exacerbate the impacts above, and would certainly translate into very high economic impacts, though these high impact scenarios are low likelihood.

Overall, it seems likely that price increases for staple products in the UK could rise with climate change, with more negative effects for higher warming scenarios especially late century, and this would translate through to a noticeable effect on household expenditures, everything else being equal, and in the absence of adaptation. The risks to UK food security are more likely to come from sudden and short-term disruptions to prices rather than lack of food availability. The importance of these effect will be significantly affected by the possibilities for substitution and per capita income growth, as well as many other factors. It is highlighted that much greater risks are possible in a 4°C world, because of the potential thresholds for much of global agriculture around this level. The resulting estimates are presented below.

Table 103 Valuation ID1: International Risks to UK food availability, safety, and quality (no adaptation).

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	High	Very High (but large range from low to VH)	Very High (but large range from low to VH)	Very High (but large range from low to VH)	Very High (but large range from low to VH)	Very High
Confidence	Low	Low	Low	Low	Low	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

There are some aspects of climate change risks and responses that have been quantified for food supply chain resilience, but there is little information on the associated costs and benefits (in aggregate). Watkiss et al., (2019[dlxxviii]) for the CCC reviewed the available options and provided some qualitative analysis of possible costs and benefits. This indicates a range of low-regret options, as well as some additional options to start the process for planning for these risks.

ID2: Opportunities for UK food availability and exports from climate impacts overseas

The CCRA3 Technical Report international chapter assessed this opportunity and reported that changes in food production overseas – from climate change - can alter the conditions under which the UK trades with those overseas countries by altering comparative advantage. Exactly how these changes result in opportunities depends on the relative importance of extreme events in reducing yields (see previous risk) versus more gradual changes in opening up new areas for production. The CCRA3 concluded that a lack of evidence over global yield increases, and difficulties in the use of marginal land and around water management, suggest that food production opportunities will not be the norm, but it did note opportunities associated with other drivers of international food systems, including plant-based meat substitutes.

For the valuation analysis, similar issues arise to risk ID1, because of the very large range of reported results in the literature, and because different results can arise from the consideration of opportunities from an economic perspective. For the valuation analysis, we consider two potential opportunities. First, there could be opportunities from enhanced food production internationally that reduces prices in the UK, i.e. the converse of the risks considered in ID1 above. It is almost certain that some areas internationally – notably more temperate areas - will see increasing agricultural opportunities on average, at least for moderate warming, and a much wider set of areas could see rising suitability (and comparative advantage) for specific agricultural crops or products. These could be particularly the case if CO_2 fertilisation effects materialise, as shown by economic studies that model such effects as a sensitivity analysis (e.g. OECD, 2015[dlxxix]) (noting that fertilisation effects are primarily in C3 plants, and less pronounced in C4 plants). These benefits are more likely to be important in the medium term (the 2050s) and more likely to be overtaken by other factors in the longer-term under higher warming scenarios (2080s. However, given the findings from ID1, it is unlikely the net overall effect of ID1 and ID2 would be strongly positive. Second, there might be opportunities for exports of food, because the UK is less affected than other world regions by climate change, and thus could gain a comparative advantage for food exports relative to other food-producing regions. These benefits were set out in the domestic opportunities identified in the natural environment and business chapters, and there is an issue of potential duplication by including here. However, it is highlighted that economic studies using partial and general equilibrium models identify that it is the changes in international areas that drive benefits in the UK (e.g. Balkovic et al. 2015, Cisar et al., 2014, COACCH, 2019) because the UK is less affected by climate change than European competitors (notably Southern Europe) and international producers.

Table 104 ID2: Opportunities for UK food availability and exports from climate impacts overseas.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	+High (but range from low to VH)	+High (but range from low to VH)	+High (but range from low to VH)	+High (but range from low to VH)	Unknown
Confidence	Low	Low	Low	Low	Low	Unknown

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

ID3: Risks to the UK from climate-related international human mobility

The CCRA3 Technical Report identifies that negative climate change impacts are likely to make some places more difficult to live and undermine development gains overseas. This may lead to displacement or migration, noting the latter is a potential adaptation response. The CCRA3 Technical Report identifies the most likely affected areas are in the Global South, due to the high dependence on agriculture and weak social safety nets. Most climate-related migration in the near future is projected to be internal (domestic), i.e. within affected countries or regions. However, increased mobility as a result of climate change is likely. The Technical Report highlights that increases in migration as a result of climate instability also present a socio-economic opportunity if migrants are able to, and supported towards effective integration.

This issue has been considered in this economic review. Migration can be voluntary or forced and can be internal, i.e. within a country, or external, i.e. from one country to another. There is some evidence (IPCC, 2019[dlxxx]) that shows that past climate extremes can be a stress multiplier for internal and external migration.

Looking to the future, climate change could also be a potential contributory factor in migration, both as an adaptation strategy, but also from forced migration. However, as the Technical Report describes, the role of climate change as a threat multiplier, and the level of migration that is projected, have both been sources of contention in the literature. This is particularly the case over forced displacement and international migration. There are no robust estimate of these effects, and the evidence in the literature includes a wide range. To explore the order of magnitude of migration to UK, some rapid analysis has been undertaken.

A first migration path of relevance is from Africa, due to the high level of potential impacts and the relative proximity to Europe. Data from the OECD Migration Database identifies that there was an annual average net flow of 16,000 migrants from Africa to the UK over the period 2000 to 2017. It is very difficult to attribute how much of this, if any, might have been due weather extremes and climate -related factors. One study of historical data from the period 1960 to 2000 (Marchiori et al (2012[dlxxxi]) suggested that approximately a third of international migration from Africa could be attributed to weather anomalies, though this does seem quite high. Nonetheless, applying these factors to the OECD data, and considering potential increases in hazards from climate change (specifically drought), and excluding the effect of population growth, it is possible to generate estimates of possible climate induced migration to the UK from Africa (Hunt et al, in COACCH 2020[dlxxxii]) and such an analysis indicates migration levels of 9,000, 12,000 and 23,000/year respectively for 1.5°C, 2°C and 3°C of global warming, additional to the recent historical annual average of 16,000 migrants.

Another migration path of potential relevance is from countries that are heavily affected by sea-level rise, in cases of no adaptation (or where adaptation is not affordable). Some of the global SLR literature has modelled the potential levels of migration, and these identify high potential levels of migration (internal or external), especially for more extreme sea-level scenarios. As an example, Lincke et al. (2019[dlxxxiii]) estimated that globally, between 50 million to 100 million people could be forced to migrate in the 2050s, and possibly double this by the 2080s, without adaptation, under various extreme SLR scenarios, though the numbers fell by an order of magnitude if adaptation was included. Many of these would migrate internally or regionally, but there would be a potential additional source of possible flows to the UK, especially for countries (including small island states) with strong UK historical links.

It is difficult to provide monetary values for this risk. There are a large range of different welfare effects of migration encompassing economic, social, cultural and environmental dimensions. It is difficult to capture all of these, though they will include changes in income for the migrants, for the population in the source country, as well as in the host country, as well as a range of wider, non-quantifiable, economic effects. There may be related effects on demand and supply in addition to non-market effects for the migrant, such as those resulting from improvements in personal security and their living environment, whilst for the host population benefits may include cultural diversity. The boundaries considered therefore also affect the overall economic effect.

For the UK CCRA, it is probably most relevant to look at the effects to the UK (and not only to the welfare of the migrants). The focus is therefore most likely on labour market impacts, impacts on productivity and growth, and impacts on the public finances or public services (Portes, 2018[dlxxxiv]). The evidence on the impact of migration on labour markets show no or extremely small impacts on wages and employment rates (Docquier et al, 2019[dlxxxv]), and similarly no or very little effect on the employment prospects of specific groups such as the low paid or low skilled. There is less evidence on the impacts of productivity and growth, though these appear to be positive (Forte and Portes, 2016[dlxxxvi]), and this also indicates a positive fiscal contribution, at least in the short-term, though this literature is dominated by analysis of European migration (see e.g. Migration Advisory Committee (2018))[dlxxxvii]. This therefore indicates that should migration emerge, the economic costs (in the UK) might be low, especially given the likely size of UK migration flows as estimated by the earlier analysis above.

Overall, the complexity of the relationships between climate variables, socio-economic development patterns, cultural practices and the nature of cross-border legal constraints on human movement to the UK make it difficult to quantify these risks, but the evidence on economic costs does not suggest major impacts. The exception to this would possibly be under a 4°C scenario, where the limited evidence suggests a step change in international impacts, and thus potential effects on the UK, though there is low confidence in how much this might affect risk magnitude.

Table 105 ID3: Risks to the UK from climate-related international human mobility.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	Low	Low	Low	Unknown	Low
Confidence	Low	Low	Low	Low	Low	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

ID4: Risks to the UK from international violent conflict resulting from climate change overseas

The CCRA Technical Report identifies that the literature on the role of climate change as a driver of conflict is contentious. Nevertheless, there is some consensus that climate can be an amplifier of conflict, whilst recognising that a range of other drivers are likely to be more important. Overseas conflict can have an indirect impact on the UK through a variety of UK overseas interests, and various transmission pathways such as governance, and finance and markets.

In terms of the monetary valuation, it is extremely difficult to provide estimates, given the highly contentious literature, as well as challenges with valuation.

Conflict can be seen as an alternative response to migration when resources integral to a community, or other group of people, become increasingly scarce. As with climate-forced migration, empirical evidence is usually qualitative and mostly based on assertion (Nordås and Gleditsch, 2007[dlxxxviii]). The risk assessment outlines the complexity of any relationship between climate and conflict, including the role of other mediating factors such as socio-economic variables, degree of democratisation and opportunities for migration.

Some quantitative data does in a study by Burke et al. (2015[dlxxxix])). This study undertook a meta-analysis of (~50) studies and investigated potential linkages between specific climate variables, e.g. mean temperature and/or precipitation, and two forms of conflict – inter-group and inter-personal. It reports evidence for a link between climatic events and violent intergroup conflict. However, this study is highly controversial and has been criticised in the literature (e.g. Buhaug et al., 2014 [dxc]), especially as other studies do not find a similar association.

If such effects did occur, the welfare effects (beyond the economy), that cascade to the UK could be through impacts on income and well-being, including security of UK citizens who are either located in the geographical area affected by conflict, or have family members and business colleagues in the area. There is also the broader economic welfare effect resulting from the conflict bringing about disruption of business activities and incomes of UK citizens.

A further non-market welfare effect could arise from the desire of UK citizens not to witness conflict – and its attendant pain and suffering – in citizens of other countries. It is possible to interpret the data given in the risk assessment – of expenditure by the UK on international conflict management, of £1.3 billion in 2018/19 - as a representation of a collective willingness to pay to avoid or reduce conflict, whether triggered by climate or other factors. It is impossible to attribute with any accuracy how much of this might be weather or climate-related, and to extrapolate to future climate change induced effects. However, a sensitivity analysis can provide some indication of possible magnitude. Using a somewhat speculative assumption, that 1% of current conflict spend can be attributed to climate change in the period to 2050s, rising to 10% by the end of the century, this would indicate a medium score initially, but becoming high in the far future (and plausibly very high if climate change began to dominate conflict and thus drive UK support to conflict management).

Table 106 ID4: Risks to the UK from international violent conflict from climate change overseas

Valuation							
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	Medium	Medium	Medium	High	High
Confidence	Low	Low	Low	Low	Low	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

ID5: Risks to international law and governance from climate change that will impact the UK

The CCRA Technical Report reports that international law provides a framework to mitigate climate risks, but it is highly dependent on states being willing to design ambitious climate plans and cooperate internationally. It also concludes that climate impacts overseas have the potential to threaten and weaken international law and governance, but identifies that quantifying these effects on the UK's interests and values is difficult. It identifies that the potential risks to international law and governance from climate change include human rights violations, contestation of well-established international rules, risks of sovereign defaults in emerging economies and new legal challenges. In turn, these risks have the potential to threaten the UK's economic, diplomatic and military interests and challenge its foreign policy of strengthening the rule-based international system and promoting human rights. However, these climate risks need to be seen in the context of other factors affecting international law and governance, and the multilateral system and states acting in their self-interest or from other factors such as globalisation.

Given the evidence on these effects, it is extremely difficult to attempt monetary valuation. Risks to international law and governance may result in welfare effects to the UK population, but it is impossible to trace quantitatively from climate change scenarios to these risks and their associated economic effects. Consequently, we do not attempt valuation scoring.

Table 107 ID5: Risks to international law and governance from climate change that will impact the UK

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Not known	Not known	Not known	Not known	Not known	Not known
Confidence	-	-	-	-	-	-

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

ID6: Opportunities from climate change (including artic ice melt) on international trade routes

CCRA3 summarises the evidence on this opportunity, reporting that opportunities from climate change to extend international trade routes are currently limited to the potential benefit from increased access to the Arctic and provision of maritime services. However, associated risks, some military in nature are also identified as a risk.

This opportunity was valued in CCRA1 (Watkiss and Hunt, 2011). This was based on a semi-quantitative analysis of the increase in the number of navigable days for the north-west and north-east passage. The analysis reported an increase in days for the north-east passage (the route most relevant for UK markets) and estimated the fuel savings from reduced journey time and reduced CO_2 emissions (and valuation using DECC carbon price valuation guidance). The benefits per voyage were estimated at £330,000, and this was multiplied by the level of large container ships from Asia, multiplied by the increase in navigable days. This resulted in a total benefit of about £70 million per year in the 2020s, with a double this value by the 2050s. This would be equivalent to a high score for the 2050s. These reduced costs could also feed through to the price of goods in the UK, or the costs of exports, with potentially important supply chain consequences as well.

Further analysis has been undertaken here for CCRA3. Again, this looks at the potential benefits that might result from an opening up of the Northern Sea Route. It is stressed that there is high uncertainty around the risk of disappearance of Arctic ice, and major differences between the disappearance of summer vs. year-round loss. This effect has often been characterised as a tipping point or tipping element. Levermann et al. (2012[dxci]) updated the probability of tipping elements, focusing on Europe, and concluded that modelling studies suggest that Arctic summer sea ice will disappear at an additional global warming of 1–2°C, but winter sea-ice cover is not likely to happen at warming of less than 5°C.

There are three specific potential benefits discussed below. These are:

- The economic effects of trade that are facilitated by a reduction in transport distance between suppliers and consumers;
- Tourism opportunities that increased access to the Arctic allows;
- Port use and development in locations that facilitate these trade and tourism opportunities.

<u>Trade effects.</u>
The lower level of sea-ice in the Northern Sea Route is projected to reduce transport distances – and therefore costs - for shipping between markets in Europe and Asia. The navigational distance between East Asia and Europe via the Arctic Northeast Passage is 30-40% shorter than the present route via the Suez Canal, 40-50% shorter than the Panama Canal route and 50-60% shorter than the route around the Cape of Good Hope. As highlighted by the analysis in CCRA1, this has the potential to significantly reduce costs.

The reduction in costs may result in increased volumes of trade between these markets and/or reductions in the prices of traded goods. One study (Bekkers et al. 2016[dxcii]) attempted to quantify the resulting economic welfare effects of these changes. Currently, 8% of world trade is routed through the Suez Canal. Bekkers et al. suggest that under the assumption that Arctic ice melt allows unimpeded sea travel via the Northern sea route by 2030, two-thirds of this volume will be re-routed. Trade flows between North-West Europe and East Asia are projected to increase by 10%, though there will be a corresponding negative economic effect on Southern Europe. Note, however, that the assumptions of year-round ice melt by 2030 are not considered plausible, and thus we apply these only to long-term warming scenarios for the 2080s, and scale-down the effects of summer ice-free transport in the 2050s in our scoring. There is also no allowance made for potential changes in storminess on these trade routes which may also have disruptive impacts.

Using a sectoral general equilibrium model, Bekkers et al. modelled the combined effect of a reduction in transport costs for existing trade and the development of newly viable supply chains. The authors estimate that global trade volumes increase by 0.21%; 15% of trade from China is projected to use the Northern sea route. The changes in total trade values with the UK from three East Asian countries are presented below. The effect on UK GDP is found to be equivalent to an annual increase of 0.24%. At GDP levels of 2019, this equates to £5.3 billion per year. The authors note that alternative assumptions including higher transport costs and the Northern sea route opening for just 6 months of the year both significantly reduce this GDP effect (as is likely in the medium term). The latter point is important, as there is a major difference in the temperature thresholds likely for loss of summer vs. year-round artic ice.

Table 108 Changes to Total Trade values to UK – no Sea Ice (%)

Country	Exports	Imports
China	12.33	8.23
Japan	12.30	7.77
South Korea	7.95	8.98

The reduction in transport distances will also have potential benefits in terms of the external costs of shipping (reduced GHG and air pollution), up until the point where shipping becomes zero carbon. These were estimated in CCRA1 and indicate that these externalities were around 10% of the direct fuel saving.

Tourism

Whilst tourism expenditures on Arctic-based activities are expected to increase with Artic ice melt and enhanced acess, no estimates exist of how large these could be. An indication, however, that this may be significant is given by the fact that a study by Maher et al. (2014[dxciii]) reports that the value of tourism to the Faroe Islands in 2014 was £60 million, half of which was as a result of sea cruise ships. Economic effects for the UK will primarily depend on the change in profits accruing to UK-owned tourist businesses.

Port Development

There is little certainty on the demand for additional port activity or port development that could develop around the UK coast as a result of the potential changes in trade and tourism activities identified above. It seems probable, however, that the scale of development would be more significant at the local/regional scale than at the national scale. It is noted that there are also risks from climate change (notably sea-level rise) to ports, which would be relevant for any changes in port infrastructure or activity.

Overall,

While these estimates are highly uncertain, they do indicate that there could be quite large positive benefits. These are estimated to be medium to high in the 2050s, and high to very high in the later time periods. These benefits are determined by the thresholds for major artic ice melt, and thus very uncertain, noting there is also difference in the literature with a much greater and earlier likelihood of summer versus year-round ice loss. There is no information to judge the benefits at the DA level, but it would be more likely that some benefits (e.g. tourism) would be heavily skewed towards Scotland.

The benefits are included in the table below, but it is stressed that these benefits need to be seen against potentially very large negative impacts from an ice free artic (e.g. loss of artic ecosystems, potential higher global warming levels, impacts on European weather, etc.). Indeed, the economic costs of Arctic land permafrost and other cryosphere elements could be extremely large (Yumashev et al., 2019[dxciv]).

Table 109 ID6: Opportunities from climate change (artic ice melt) on international trade routes.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	+Medium	+High	+High	+Very High	+Very High
Confidence	Low	Low	Low	Low	Low	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

<u>Adaptation</u>
The analysis above shows potential benefits above. There is a question whether these benefits will be fully realised by non-government adaptation alone, and it is likely that higher benefits could be achieved for the UK (as compared to competitor coastal countries) through some enabling actions from government, which would have likely low costs.

ID7: Risks associated with international trade routes

The CCRA3 Technical Report considers the potential effects of climate change on all traded goods. It reports that climate-related disruption to non-food supply chains may occur in production facilities (e.g. floods affecting factories or mines), but it highlights it is more likely to impact on supply-chain logistics. These risks are important in globalised supply chains which are characterised by "just-in-time" delivery, which are high efficiency but have low redundancy.

This potential risk has received more attention since CCRA1, but there is relatively little economic information on the risk, as identified in a recent literature review (COACCH, 2018[dxcv]). However, in the UK, several studies have concluded that climate change impacts transmitted by international trade might represent a similar or even greater threat for some parts of the UK economy than domestic climate change impacts (UK Foresight, 2011; PwC, 2013; West et al., 2015[dxcvi]).

The UK has extensive networks of supply chains internationally. As well as food, there are many other goods traded, which include domestic and international supply chains, including imports and exports of cars, medicinal and pharmaceutical products, refined oil, clothing, etc. UK Trade represents 63.5% of GDP, and the UK imports more than it exports, with imports worth £718.3 bn and exports £689bn, resulting in a small trade deficit of 1.3% of GDP in 2019 (DIT, 2020[dxcvii]), although a large proportion of this trade is with Europe.

Through these international supply chains, distribution networks and global markets, the UK is exposed to the risks of extreme weather around the world. Climate change is expected to increase the risk of weather-related disruptions, particularly for supply chains and distribution networks that involve more vulnerable countries. However, an important issue is how trade might change in the future – not only as a result of Brexit but more in general as a result of increasing globalisation - and the balance between domestic and international supply chains. While this is all uncertain, some estimates suggest world trade volumes will increase, hence the exposure of supply chains to climate risks would be expected to proportionally increase. MoD (2018[dxcviii]), for example, estimated that by 2050 shipments of raw materials could double to Western economies and quadruple to other regions, and the global freight trade could grow between 330-380%.

There is some evidence in terms of current weather-related disruption to supply chains. A principal example is the floods that affected Thailand extensively in 2011, impacting on the supply of manufacturing components – particularly in the automotive and high-tech sectors – which led to global disruption in these sectors and price increases of 20-40 percent. The country that was hardest hit was Japan – which had a number of plants in Thailand that were severely disrupted – leading to profit projections of Toyota being cut by US$2.5 billion. The floods also affected Thailand's role as the world's 2nd largest producer of hard disk drives, accounting for 43% of world production. Many of the factories that make hard disk drives were flooded leading to worldwide shortages of hard disk drives in the short-term, increasing the price of desktop drives by 80–190% and mobile drives by 80–150%, with losses for Reinsurers of around $10 billion (Haraguchi et al,. 2015[dxcix]). The World Bank estimated that the total economic cost of flood damage in Thailand was US$45.7 billion.

There have been some studies of supply chain and procurement risks, focusing on disruptions and delays in delivery and transport due to extremes. Lühr et al. 2014[dc] review the literature on disruptions of production. They report estimates that 70% of damages by extreme weather events are linked to supply chain and procurement risks (such as disruptions and delays in delivery) with the remaining 30 % of damages due to direct physical damages of the production sites. They also cite other studies that find that 60% of companies affected by production disruptions show a reduction in turnover (of around 5%) and return on sales (of 4%) in the following year.

There has also been analysis of supply chain risks using input output (I-O) models (Wenz and Levermann, 2016[dci]). One recent I-O analysis was undertaken by the COACCH project (2019[dcii]). This assessed input-output connectivity between 25 sectors[33] and 178 countries from the EORA database, along with data on extreme weather. It found an increase in international supply chain linkages over time (from 1990 to 2015), and that sectors with strong supply chain interlinkages are regularly hit by natural disasters. It found that productivity shocks transmitted over a supply chain significantly reduce average sectoral export performance: on average an increase in supply chain shocks resulting from a RCP4.5 climate scenario over the current century reduces an average sectoral export value by around 11%.

Looking forward to consider climate change, it found countries' sectoral exports are negatively affected by this risk, which could reduce a sector's export value by up to 16 percent. However, these impacts vary strongly between countries and sectors. The largest impacts on exporting countries were projected for the tropics and subtropics, due to the stronger projected climate impacts, which are then transmitted over interregional supply chain connections. The effects on the value of the UK's export value were found to be slightly higher than the EU average over the different emission scenarios and future time periods considered. Whilst these changes have not been converted to annual welfare change-equivalents these indicative results point to these effects being potentially significant in terms of the impact on future GDP.

Table 110 Impacts on Sectoral Export Value (% change) under future RCP scenarios for the UK

Time period	RCP2.6	RCP4.5
2020-2040	-10.98	- 11.05
2041-2070	-12.52	-13.65
2071-2100	-11.65	-14.93

Source: COACCH project (2019[dciii]; 2020[dciv]).

The ImpactChain project undertook at relevant study in Germany looking at these issues. It estimated that imports from non-EU regions could decline by up to 2% by 2050 due to climate change, but also

[33] Agriculture, Fishing, Mining and Quarrying, Food & Beverages, Textiles and Wearing Apparel, Wood and Paper, Petroleum, Chemical and Non-Metallic Mineral Products, Metal Products, Electrical and Machinery, Transport Equipment, Other Manufacturing, Recycling, Electricity, Gas and Water, Construction, Maintenance and Repair, Wholesale Trade, Retail Trade, Hotels and Restaurants, Transport, Post and Telecommunications, Financial Intermediation and Business Activities, Public Administration, Education, Health and Other Services, Private Households, Others, Re-export & Re-import.

that exports to non-EU regions could decline by up to 0.3%, leading to a reduction in national GDP and welfare despite higher EU trade (see Tröltzsch et al., 2018[dcv]). There have also been a number of case studies on specific regions and sectors, such as the impact of losses in the automobile industry from 2011 flooding in Thailand (Haraguch and Lall, 2015[dcvi]).

This evidence suggests this risk could therefore be important, but it is difficult to provide quantitative estimates with confidence. As identified above, these effects will include disruption to production processes or disruption to transportation of goods, with the economic effect likely to be in the form of a loss of supply of goods or an increase in their price, which would lead to welfare losses for UK consumers. Over the long-term, importers may diversify their supply chains to minimise these risks, where this is possible.

Finally, there has also been some analysis of the impacts of climate change on water resource supply chains, focused on production risk as a result of water resource availability in other countries. Hunt et al. (2014[dcvii]) estimated embodied water imported to the UK for 25 economically significant and climate sensitive sub-sectors, (see footnote), then explored the current and future susceptibilities of these sub-sectors under climate change. In 2010, these products represented 31% of total UK imports by value ($), and 12.8 billion m^3 of embodied water. This concluded that climate change-induced changes in international comparative advantage were therefore likely to lead to evolving trade patterns and relations, as well as costs, but these were not quantified.

The lack of evidence makes it difficult to provide robust estimates, especially as major extremes (such as the Thailand floods) are infrequent. The scores in the table are therefore indicative only.

Table 111 ID7: Risks associated with international trade routes

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	Medium	Medium-High	High	Very High	Very High
Confidence	Low	Low	Low	Low	Low	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Adaptation

The discussion of adaptation is related to the business risk B6, and involves many of the same potential responses, though there is the potential for additional adaptation in trade policy to address international risks, as well as international supplier diversification.

ID8: Risk to the UK finance sector from climate change overseas

The Technical Report of the CCRA3 reports on the potential transmission of international climate risks to the UK through the finance sectors. It concludes that there may be significant financial exposure to extreme weather impacts in other countries, that could cascade through to the UK, especially through insurance markets. There is a particular risk as London operates a global insurance market with products covering both direct climate change events such as agriculture insurance as well as indirect impacts such as business interruption. It concludes that this could have a significant impact on all types of asset classes and potentially put further stress on UK pension funds.

The economic impacts of these potential risks are also considered in Chapter 6 around business risks to the finance sector (B4), and the same sectors of the financial markets are relevant, i.e. finance, insurance, investment and banking.

The UK is currently one of the leading exporters of financial services across the world and it is one of the most exposed countries to climate change, due to its high financial leverage and central role in the global financial network (Mandel et al, 2020[dcviii]).

As reported in Chapter 6, there are potential risks for the financial and banking sectors, because they hold or invest in international assets, companies or investments that may be vulnerable to the changing climate. The Economist Intelligence Unit (2015[dcix]) estimated the value at risk, as a result of climate change, to the total global stock of manageable assets as $4.2 trillion between now and the end of the century. The study also reported that the asset management industry is particularly subject to tail risks: lower probability but higher impact losses. A further analysis by Mercer (2015[dcx]) also estimated the impact on return expectations between 2015 and 2050 when climate considerations were included, finding climate change risks could impact investment returns. As highlighted in Chapter 6, there is therefore a high level of potential international exposure in the UK financial sector to these risks.

There are also the risks from international exposure in insurance. For example, the effect of the Thailand floods in 2011 to the manufacturing sector cost USD$2.2 billion in insurance claims for London (Lloyds, 2018). Globally, only 50% of losses are insured, and underinsurance is expected to increase as extreme events become more frequent.Lloyds (2015[dcxi]) developed a number of scenarios to explore the potential materiality of extreme shocks within the food system and found a number of different scenarios that could impact the UK insurance market. The UK insurance and re-insurance industry will therefore be exposed to the projected increase in frequency of extreme weather events globally, where it provides cover to such events, and the risks are not internalised in premiums (noting that climate change is likely to change levels of insurance, as well as insurance markets, potentially significantly, to address these risks).

The global sovereign debt market is one of the largest asset classes in the world. Climate related disasters (e.g. major storms, major floods) can have a large negative impact on government finances, and they are a major cause of contingent liabilities, at least for emerging markets. Major climate extremes already affect sovereign credit ratings today, and in turn the cost of debt and cost of capital. In a few cases, climate-related extreme events have led to a direct cause of sovereign defaults (Moody's, 2016[dcxii]). Climate change is projected to increase the intensity and potentially the frequency of these extreme climate events (as reported in the CCRA3 Technical Report (Chapter 6)). The major credit rating agencies have identified climate change as a global mega-trend that could impact sovereign creditworthiness. A number of the rating agencies are starting to consider climate risk in credit worthiness assessments, both at the country level and also for individual companies (Moody's, 2017[dcxiii]: S&P Global Ratings, 2015: 2017[dcxiv]). Sovereign debt investors are exposed to a range of climate change risks that are typically not well understood or incorporated in the investment process. This has started to be recognised within the sector, and tools to managed such risks have started emerging (e.g. FTSE Russell[dcxv]). There are studies that highlight that climate change could potentially increase the risk of sovereign defaults or downgrades in emerging economies (Malluci, 2020[dcxvi]), which could affect investments. Climate vulnerable countries could experience an increase in their cost of debt and cost of capital (ICBS and SOAS, 2018[dcxvii]), which will also spill-over into increases in the return requirements that investors have. There has also been some analysis which indicates climate change could potentially increase the risk of sovereign defaults in emerging economies (Cevik & Jalles, 2020[dcxviii]; Malluci, 2020[dcxix]) and a major concern for South Asia (Volz et al., 2020[dcxx]). Importantly, recent analysis finds that investors are still paying little attention to climate change risks in their investment practice (CFA, 2020[dcxxi]).

Overall, given the UK's role in financial services globally, there are very high potential risks. In practice, some of these can be mitigated by changing investment strategies, driven by increasing awareness of such risks. At the same time, it may well be the case that new financial instruments can be developed, thereby presenting an opportunity for the development of the sector, both domestically and internationally (see Chapter 6 and TCFD).

The welfare effects from these risks relate to the loss of profits to UK companies, and thus, the contribution of financial services to the public finances. The financial sector accounts for around 10% of GDP. Total UK overseas insured risk equates to about 25% of the total UK insured risk, whilst banking service export earnings from overseas lending was 35% of total UK banking lending earnings. Overseas assets managed by UK financial services are equivalent to 30% of total UK asset holdings. These data therefore suggest potentially sizeable climate-related risks. There is little quantitative evidence, but the information above implicitly suggest that the scoring of the risks should be very high.

Table 112 ID8: Risk to the UK finance sector from climate change overseas.

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	High	Very high	Very high	Very high	Very high	Very high
Confidence	Low - medium	Low	Low	Low	Low	Low

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

ID9: Risk to UK public health from climate change overseas

The CCRA3 Technical Report sets out that this risk is focused mostly on the threat of vector borne disease (VBDs) internationally to the UK. These can arise initially from human infections acquired abroad and import of infected vectors or animals. It identifies two factors that determine climate-induced VBD risk: changes in climatic conditions that encourage changes in incidence rates, and the initial rates of prevalence across a given population. It reports that the risk is high where the vector has been introduced recently and has become endemic. There are a number of examples where UK visitors to parts of Western Europe now bring the risk of exposure to new diseases, illustrating the risk transmission pathway. The change in the UK climate is also relevant, as it may change enough to allow local transmission of diseases once they arrive. The Technical Report identifies the greatest risks are for blood sucking arthropods, namely mosquitoes, midges and ticks, and West Nile virus (WNV) and viruses that can be transmitted by Aedes albopictus (a species of mosquito), including dengue and chikungunya virus. The recent discovery of ticks carrying tick borne encephalitis virus in the UK is a further indication that exotic diseases are becoming established. The CCRA3 Technical Report highlights that whilst any single disease presents a low likelihood, the full set of transmission pathways across all health risks result in a medium level of risk. Similarly, whilst in any given year the risk may be low, it increases in magnitude as time goes on.

The valuation of the impacts on public health of these diseases is possible, if there are quantified estimates of the risks. The welfare costs of these illnesses are based on the medical treatment costs, the costs of lost productivity in paid or voluntary work, and the pain and suffering associated with these illnesses. At the present time, VBD cases reported have been acquired as a result of travelling to endemic areas overseas. The number of cases is low (there are a few hundred cases of dengue fever each year, and lower numbers of chikungunya, usually under a hundred, though there are year to year variations, PHE, 2013[dcxxii]). The potential increase in these cases is projected to rise with climate change, but the economic valuation is likely to be low provided that cases only arise from travel, i.e. if these do not become endemic. For example, if we were to assume – as an upper limit - that 5 deaths resulted annually as a consequence of climate change-induced VBDs, then using the UK Government's valuation of a prevented fatality, an annual impact of around £10 million would result.

The Technical Report considers that the current system of control and treatment is sufficient to contain identified outbreaks. As long as this system is maintained future outbreaks under climate change are likely to be minimal, and the overall risk remains low. The magnitude scores in the table below reflect this. However, if these diseases became endemic, this would lead to very different scores. The potential spread of tick-borne disease could be an exception, as this is endemic in many parts of Europe, and range and prevalence are changing due to climate change. There are some estimates of the costs of the disease, as well as preventative costs (vaccination) and willingness to pay studies to avoid the disease (Slunge et al., 2015[dcxxiii]). The current market price of vaccination (£100 per person) means that the costs of disease prevention in other European countries where TBE is endemic are high can be tens of millions per year, suggesting that total costs in the UK would be similar if the disease became endemic. This influences the scoring in the table below in later years to a potential medium score. More recently, there has been some willingness to pay surveys in European countries with high levels of tick-borne disease, which indicate high values for reductions in disease (Euro 106 for a 25% reduction of ticks and Euro 153 for a 50% reduction of ticks) (Ščasný et al., 2020[dcxxiv]). Again, this suggests costs are high if diseases become endemic / widespread in the UK.

There is also the potential risk of new diseases emerging and spreading internationally, from cases where climate change has had an influence. Indeed, there is a suggestion by one paper that the SARS-CoV-2 pandemic (Beyer et al. 2021)[dcxxv] rapidly increased in Yunnan province in China as a result of changes in vegetation cover, which arose from changes in climate conditions over the last century. While considerable caution should be taken in any such attribution to climate change, this does highlight the potentially high costs from climate related public health risks.

Table 113 ID9: Risk to UK public health from climate change overseas

Valuation						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK	Low	Low	Low	Medium	Medium	Medium
Confidence	High	Low - Medium	Low - Medium	Low - Medium	Low - Medium	Low - Medium

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

<u>Adaptation</u>

The main benefits of further action are in enhanced monitoring and surveillance systems, including early warning, and these can be considered a low-regret option (WHO, 2013).

ID10: Risk multiplication from the interactions and cascades of named risks across systems and geographies

The final international risk considered in the CCRA Technical Report moves away from “sectoral risks” to consider the potential for hazards to create cascading risks that cross sectors and geographies. These “systemic risks” can arise from highly inter-connected sectors and economies. The Technical Report identifies that the potential for systemic risks is growing, but there is insufficient literature that link specific events (hazards) to specific impacts. Nonetheless, it considers there are potentially a very large number of hazards that could drive systemic risks across the world, and while these individually may be low probability, the likelihood is high that over time, something will happen - even if the something is unpredictable. This makes the risk very challenging for valuation, as it has no identifiable, separate, welfare effects. It is therefore presented as unknown, though following the logic in the Technical Report would suggest that it could be high to very high, especially in late century.

Table 114 ID10: Risk multiplication from the interactions and cascades.

Valuation (Confidence in brackets)						
Country	**Present Day**	**2050s, on a to pathway stabilising at 2°C by 2100***	**2050s, on a pathway to 4°C at end of the century#**	**2080s, on a to pathway stabilising at 2°C by 2100***	**2080s, for 4°C world at the end of the century#**	**Low likelihood – high impact**
UK		Unknown	Unknown	Unknown	Unknown	
Confidence		Unknown	Unknown	Unknown	Unknown	

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year. DA values are presented as absolute values (not relative scoring as in CCRA3.

Summary and Discussion of International Theme

In the sub-sections above, the ten priority risks and opportunities to the UK attributable to climate change occurring outside of the UK are considered in terms of their potential impacts on economic welfare. These ratings are summarised in the table below.

The international theme is challenging for valuation. This is partly because of the low quantitative evidence base, and high uncertainty around risks and opportunities, but also because the risks may not be ones in which economic metrics are easy to identify (and to value). The confidence for this theme is particularly low, and there are low confidence scores across all risks and opportunities. There are some potentially large international risks, which could be plausibly £billions/year, notably the risks to food availability (ID1) and risks to the financial sector (ID8). For international food chains, previous food price shocks in the UK have affected a large number of consumers, and thus in aggregate, they can lead to very high economic costs (through rising prices rather than availability of food). For the financial sector, there are potentially large risks, especially because of the UK's central role in the global financial network, though this might also generate some potential opportunities.

There are two risks that are highly contentious in the literature (migration, ID3, and conflict, ID4). The analysis here – while very indicative – indicates that in terms of their economic impact in the UK (only), they may not be high - though we stress there could be very high economic costs in the countries of origin. The other risks generally seem to be low in monetary terms, including public health (ID9, vector borne diseases), and there is one large positive opportunity, from the artic trade route opening up. Finally, there are a further set of risks that are much more difficult to quantify and value, which could also be important, but for which there is no evidence. This includes potential risks on international law (ID5), as well as multiplication effects (ID10).

Taken overall, the analysis suggests that while the economic costs of international risks of climate change will rise through the next few decades and be very high in total, the impacts of these overseas on welfare in the UK (domestically) may not be as high as previously reported, at least at mid-century. The exception to this would be under a 4°C scenario, where the limited evidence that does exist suggests a step change in international impacts, and thus potential effects on the UK.

Table 115 Summary of Valuation Scoring for International Risks and Opportunities.

Risk	Present Day	2050s, on a to pathway stabilising at 2°C by 2100*	2050s, on a pathway to 4°C at end of the century#	2080s, on a to pathway stabilising at 2°C by 2100*	2080s, for 4°C world at the end of the century#	Low likelihood – high impact
ID1: Risks to UK food availability	High	Very High (but large range from low to VH)	Very High (but large range from low to VH)	Very High (but large range from low to VH)	Very High (but large range from low to VH)	Very High
ID2: Opportunities for UK food availability	Low	+High (but large range from low to VH)	+High (but large range from L to VH)	+High (but large range from L to VH)	+High (but large range from L to VH)	Unknown
ID3: Human mobility	Low	Low	Low	Low	Unknown	Low
ID4: violent conflict	Low	Medium	Medium	Medium	High	High
ID5: law and governance	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
ID6: Opportunities international trade routes	Low	+Medium	+High	+High	+Very High	+Very High
ID7: Risks international trade disruption	Low	Medium	Medium-High	High	Very High	Very High
ID8: Risk finance sector	High	Very high	Very high	Very high	Very high	Very high
ID9 Public Health	Low	Low	Low	Medium	Medium	Medium
ID10 Multiplication	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown

Very high = £billions/year. High = £hundreds of millions/year. Medium = £tens of millions/year. Low = £<10 million/year.

Discussion

The results above are considered through a number of key questions.

What are the largest risks and opportunities?
A first finding is that a significant number of known climate threats have very high (aggregate) economic costs (£billions/year) in the UK, even by the mid-century. These include river and surface water flooding to residential properties, business and infrastructure, and the impacts of sea-level rise, coastal flooding and storm-surge to the same receptors. They also include the impact of extreme heat, notably in terms of health and well-being (including fatalities) and overheating in the built environment (residential and business), impacting either in terms of discomfort / reduced productivity, or increasing cooling demand for households and business. The other main hazard, that of water (and the water supply-demand balance) is potentially high in monetary terms in mid- and late-century, although it varies between regions (with England projected to be the most affected). This is projected to occur even though water management plans are already integrating climate change.

There are also large potential costs to business and industry. The evidence in this area has increased since CCRA1, not least because of the interest in climate related financial disclosures. The largest risks are still associated with floods, as well as to financial services, but there is a much wider set of linkages that mean a broader set of risks could be important. Indirect risks (from extremes), cascading risks (to infrastructure) and supply chain risks (business) all potentially involve very high economic costs, though valuation studies are at an early stage. It is highlighted that the focus of this analysis has been on the aggregate values at the national scale. Some risks may not be that large at this scale, but could have high localised costs and have large impacts on particular areas or groups. This cautions against focusing only on the largest risks.

There are almost certainly very large risks to the natural environment, again of the order of £billions/year. These arise from a wide range of risks (including both slow-onset and extreme events), though the evidence base for valuation remains low, both in quantitative and economic terms.

At the same time, there are a number of large economic benefits (also £billions/year) for the UK, again by mid-century, associated with reductions in cold-weather related impacts. These include reduced winter heating demand as well as health and well-being benefits. However, these positives should not be summed against the negatives above, for the same receptors, because they affect different geographical areas as well as different groups, and also require contrasting adaptation strategies. There are also potential benefits (opportunities) for some areas of trade, as the UK may gain a comparative advantage either because the climate becomes more suitable in the UK, or because climate change impacts are greater in competitor countries. These include, for example, tourism and some agricultural products. There are also likely to be some opportunities for the finance sector, and for adaptation services more generally, both with the UK, and for UK businesses overseas. These could help strengthen the case for political engagement in adaptation.

A second key finding is that there is a clear step change in the economic costs of climate change in the UK for a 4°C versus a 2°C future. However, this is often masked in the tables above by the valuation scoring: once a risk is rated as very high (>£1billion/year), the large differences between the two futures (i.e. 2 vs 4°C) are not evident. The underlying valuation (see the chapters) shows large differences in the actual economic costs between the 2 and 4°C worlds, even by mid-century. By the late century the differences are extremely large. This highlights the benefits of global mitigation for the UK.

This can be seen in the figure below, which presents the absolute values for a number of key risks. This shows the increase over time, especially in later time periods for a 4°C scenario.

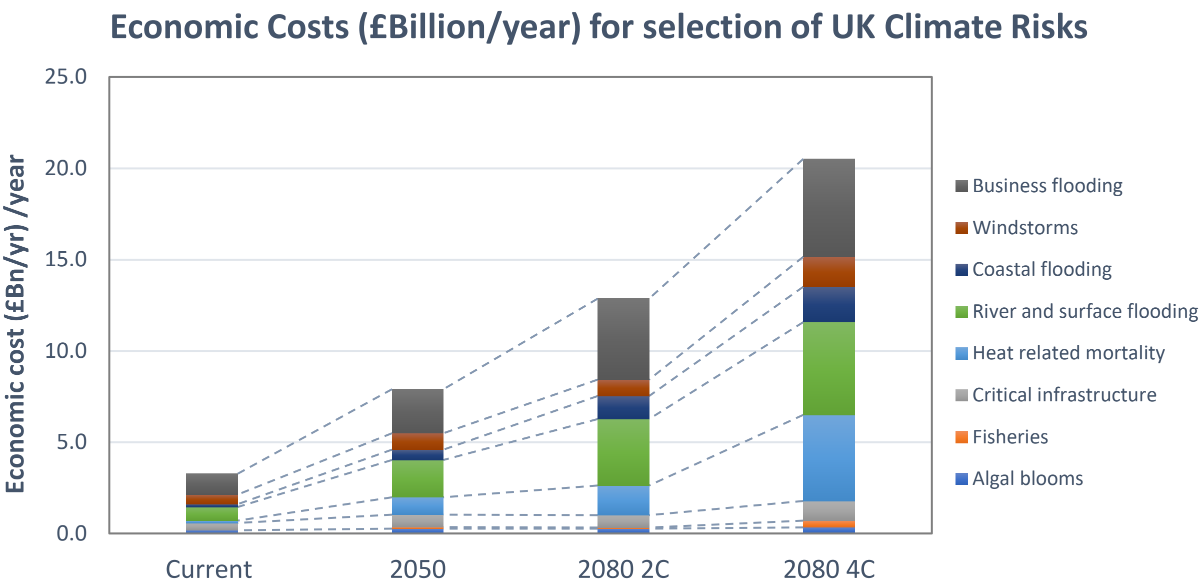

Figure 25 **Annual economic costs of climate change in the UK for a selection of risks.**

Values include climate and socio-economic change, presented in current prices with no discounting, central values. Note these values are taken from different sources, and thus some care must be taken in the direct comparison, because they use different climate model outputs, scenarios and assumptions.

It is highlighted that there are very large ranges of economic costs (or benefits) for all the risks (and opportunities) above, because of the high uncertainty around future climate change. The valuation scores above present the central estimates, but across the UKCP probabilistic projections, the range of outcomes (and thus values) is very large, and sometimes even changes in sign. This uncertainty is important at the mid-century, at which point in time the climate model uncertainty is usually larger than the difference between a 2 versus 4°C pathway. It is not possible to present the full range of potential economic costs easily and succinctly. It is stressed that for some adaptation decisions, the range of future outcomes, including the upper 90th percentile outcome, will be more important than that of the central value. This also highlights the need to consider uncertainty for any subsequent adaptation assessment. However, while this uncertainty exists, the key message from the valuation analysis is robust, i.e. climate change will have high economic costs in the UK. Further, this uncertainty is not a reason for inaction, and adaptation can be designed to take this uncertainty into account.

What has changed since CCRA1?

One robust conclusion is that the size of the economic costs of climate change in the UK, as assessed by CCRA3, is larger than assessed in CCRA1. A simple comparison between the two valuation assessments is shown below. The number of very high and high risks (but also the high and very high opportunities) is much larger in CCRA3. As an example, there were only three very high risks (>£1Billion/year) identified in CCRA1 but over fifteen in CCR3.

	2020s	2050s	2080s
Loss of staff hours due to high internal building temperatures	-H	-H - VH?	-H - VH?
Residential properties at significant risk of flooding	-H	-H	-VH
Non-residential properties at significant risk of flooding	-H	-H	-VH
Insufficient summer river flows to meet environmental targets	-H	-H	-H
Climate risks to investment funds	-H?	-H?	-H?
Energy demand for cooling	-M	-H	-H
Summer morbidity due to higher temperatures	-M	-H	-H
Hospitals and schools at significant risk of flooding	-M	-H	-H
Distribution of marine alien/invasive species	-M	-M	-H
Public water supply-demand deficits	+M	-H	-H
Risks to species and habitats due to coastal evolution	-M	-M	-H
Risks to coastal habitats due to flooding	-M	-M	-H
Overheating of buildings	-M	-M	-H
Power stations/sub-stations at significant risk of flooding	-M	-M	-M/H
Increased subsidence risk due to rainfall changes	-M	-M	-M
Agricultural land lost due to coastal erosion	-M	-M	-M
Energy transmission efficiency capacity losses due to heat - over ground	-M	-M	-M
A decrease in output for businesses due to supply chain disruption	-M	-M	-M
Extreme weather event (flooding and storms) mortality	-M	-M	-M
Extreme weather event (flooding and storms) injuries	-M	-M	-M
Heat related damage/disruption to energy infrastructure	-L/M	-L/M	-L/M
Increased ocean acidification	-L	-M	-M
Decline in marine water quality due to sewer overflows	-L	-M	-M
Risks of human illness due to marine pathogens	-L	-M	-M
Forest extent affected by red band needle blight	-L	-L/M	-M
Summer mortality due to higher temperatures	-L	-M	-M
Risk of pests to biodiversity	-L	-M	-M
Risk of diseases to biodiversity	-L	-M	-M
Species unable to track changing 'climate space'	-L	-M	-M
Changes in species migration patterns	-L	-M	-M
Biodiversity risks due to warmer rivers and lakes	-L	-L	-M
Generalist species more able to adapt than specialists	-L	-L	-M
Wildfires due to warmer and drier conditions	-L	-L	-M
Mortality due to summer air pollution (ozone)	-L	-L	-M
Disruption to road traffic due to flooding	-L	-L	-M
Flood risk for Scheduled Ancient Monument sites	-L	-L	-M
Changes in wheat yield (due to warmer conditions)	+H	+H	+H
Reduction in energy demand for heating	+H	+H	+VH
An expansion of tourist destinations in the UK	+H?	+H?	+H?
Decline in winter morbidity due to higher temperatures	+H	+H	+VH
An expansion of tourist destinations in the UK	+H?	+H?	+H?
Decline in winter mortality due to higher temperatures	+M	+M	+H
Changes in sugar beet yield (due to warmer conditions)	+M	+M	+M
Opening of Arctic shipping routes due to ice melt	+L	+M	+M

Risk / Opportunity	2050s		2080s, 2°C		2080s, 4°C	
NE5. Risks to natural carbon stores and sequestration	VH		VH		VH	
I1. Risks to infrastructure networks from cascading failures	VH		VH		VH	
H1. Risks to health and wellbeing from high temperatures	VH		VH		VH	
H3a River and surface flooding	VH		VH		VH	
B1. Risks to business from flooding	VH		VH		VH	
B4. Risks to finance, investment and insurance	VH		VH		VH	
ID8: Risk finance sector	VH		VH		VH	
I2. Risks to infrastructure services from flooding	H – VH		H - VH		VH	
H5: Risks to building fabric	H		VH		VH	
H6b: Risks from increased summer household energy demand	H		VH		VH	
ID7: Risks international trade disruption	M		H		VH	
B5. Risks to business from reduced employee productivity	M		M		H - VH	
I12. Risks to transport (in addition to flooding)	M – H		M - H		M - H	
NE4. Risk to soils.	H		H		H	
NE6. Risks to and opportunities for: *Agriculture*	H	+H	VH	+VH	VH	+VH
ID1: Risks to UK food availability	VH	+VH	VH	+VH	VH	+VH
I10. Risks to energy (in addition to flooding)	H-VH	+H-VH	H-VH	+H-VH	H-VH	+H-VH
I11. Risks to offshore infrastructure from storms and high waves	H-VH	+H-VH	H-VH	+H-VH	H-VH	+H-VH
N11.Risks to freshwater species and habitats	H		H		H - VH	
I8. Risks to public water supplies from reduced water availability	H		H		H	
H3b Coastal flooding	H		H		H	
B3. Risks to businesses from water scarcity	H		H		H	
NE7. Risks to agriculture from pests, pathogens and invasive	M		H		H	
H10a: Risks to household water supplies	H		H		H	
I5. Risks to transport networks from slope / embankment failure	M – H		M - H		H	
NE8. Risks to forestry from pests, pathogens and invasive	M		M		H	
NE14. Risks to marine species, habitats and fisheries	M		M		H	
I13. Risks to digital	M		M		H	
ID4: Violent conflict	M		M		H	
NE16. Risks to marine from pests, pathogens and invasive	M		M		M	
NE17. Risks and opportunities to coastal species and habitats	M		M		M	
I3. Risks to infrastructure services from coastal flooding	M		M		M	
I4. Risks to bridges and pipelines from flooding and erosion	M		M		M	
I6. Risks to hydroelectric generation from low or high river flows	M	+M	M	+M	M	+M
I7. Risks to subterranean and surface infrastructure	M		M		M	
NE6. Risks to and opportunities for: Forestry	L - H		L - H		L - H	
B2. Risks to business and infrastructure from coastal change	M		M		M	
H8: Risks to health from vector-borne disease	L - M		M		M	
ID9 Public Health	L		M		M	
N12. Risks to freshwater from pests, pathogens and invasive	L		L		M	
H4: Risks to viability of coastal communities from sea level rise	L		L		M	
H7a: Risks to health and wellbeing from changes in air pollution	L		L		L	
H9: Risks to food safety and food security	L		L		L	
ID3: Human mobility	L		L		L	
NE1. Risks to terrestrial species and habitats	Unknown		Unknown		Unknown	
NE2. Risks to terrestrial from pests, pathogens and invasive	Unknown		Unknown		Unknown	
NE3. Opportunities from new species colonisations (terrestrial)	Unknown		Unknown		Unknown	
N10. Risks to aquifers and agricultural land from sea level rise	Unknown		Unknown		Unknown	
NE18. Risks and opportunities to landscape character	Unknown		Unknown		Unknown	
I9. Risks to energy generation from reduced water availability	Unknown		Unknown		Unknown	
H7b: Risks to health / wellbeing from changes in aeroallergens	Unknown		Unknown		Unknown	
H10b: Risks to water quality	Unknown		Unknown		Unknown	
H11: Risks to cultural heritage	Unknown		Unknown		Unknown	
H12: Risks to health and social care delivery	Unknown		Unknown		Unknown	
H13: Risks to education and prison services	Unknown		Unknown		Unknown	
ID5: Law and governance	Unknown		Unknown		Unknown	
ID10 Multiplication	Unknown		Unknown		Unknown	
B6. Risks to business from disruption to supply chains / dist	Unknown		Unknown		Unknown	
H2. Opportunities for health and wellbeing from high temp	+ VH		+ VH		+ VH	
B7. Opportunities for businesses from changes in demand	+VH		+VH		+VH	
H6a: Opportunities reduced winter household energy demand	+ VH		+ VH		+ VH	
NE9. Opportunities for agricultural and forestry productivity	+H		+H		+VH	
ID2: Opportunities for UK food availability	+H		+H		+H	
ID6: Opportunities international trade routes	+M		+H		+VH	
NE15. Opportunities to marine species, habitats and fisheries	+M		+M		+H	
N13. Opportunities to freshwater species and habitats	+L		+L		+M	

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Figure 26 **Comparison of overall valuation for CCRA1 (left) and CCRA3 (right).**

It is difficult to directly compare CCRA1 and CCRA3, because the list of risks and opportunities has changed significantly, but in general, when there is a similar risk description, the CCRA3 score is higher than CCRA1.

These findings – of increasing costs - are mirrored in the international literature, where there has been a general trend of increasing economic costs reported, whether in the global economic models (e.g. the rising social cost of carbon, e.g. Nordhaus, 2017dcxxvi) or in regional or national studies (e.g. for the economic costs of climate change in Europe, Szewczyk et al., 2020dcxxvii). This is happening for a number of reasons.

There have been some changes in the impacts literature that have led to assessments finding higher impacts. In general, there is more consideration of extreme events in physical studies than there was at the time of the CCRA1, and these tend to lead to negative impacts. These tend to shift the overall narrative away from a general trend of winners and losers (from slow-onset change) to primarily a negative impact of climate change in the UK. There is also more information and evidence on the indirect costs of many risks, which increase economic costs, especially for major extreme events.

In terms of hazards, the timing of the CCRA3 means that the new UKCP18 projections have not fed through to many new impact studies. The full consideration of UKCP18 (see the CCRA3 Technical Report) does identify cases where risks have changed, and as new valuation studies emerge, this may increase the monetary valuation estimates further. As an example, the risk of sea-level rise has increased significantly in physical terms since CCRA1 with much higher projections (IPCC, 2019dcxxviii), but this is not yet feeding through to higher economic costs as few studies have incorporated the more recent projections at this time.

In addition, more of the studies undertaken since CCRA1 have factored in future socio-economic change. This has a major influence on the size of the results. This can be illustrated with the analysis undertaken for floods: including future population can increase future damages by 20 – 30%, but the inclusion of future economic growth and value-at-risk can double future damages. This also highlights the need to have a more thorough and consistent approach for accounting for these socio-economic effects in future studies.

The higher costs are also influenced by the fact there is more economic evidence available in the literature, and thus more valuation studies to report on. It is also noted that the move to a broader definition of risks in CCRA3 crowds in more potential impacts, and thus inevitably will lead to higher costs (e.g. considering all pest and disease risks to forests in CCRA3, versus only red needle blight in CCRA1).

There is, however, one possible exception to the trend of larger impacts in CCRA3 . This is for international risks. CCRA1 only covered domestic risks, and so international risks were omitted. However, at the time of CCRA1, other studies were reporting that the international risks of climate change, i.e. that happened overseas, would cascade back and lead to impacts in the UK that were as large as risks occurring directly (domestically) within the UK (e.g. Foresight, 2011dcxxix). Based on the valuation evidence presented here, this does not seem to be the case for warming of 3°C or below, i.e. domestic risks appear much larger than international risks cascading back to the UK, though this may be due to the lack of evidence, and the difficulty in quantifying these pathways. We also note that this may not be true for business (and certainly some business sectors). We also stress that the economic costs of intentional risks in the countries where these impacts occur (overseas) will be extremely large, and that it is likely that international risks could rise disproportionately for a 4°C pathway later in the century, and at this point, this finding is likely to change.

Finally, an interesting finding from the economic analysis is that when markets are involved, and notably for the provisioning services (agriculture, fisheries and forestry), economic studies using partial or general equilibrium modelling indicate different results to the physical analysis. These economic studies tend to be much more positive for the UK, because they factor in trade and price effects, and project that other countries in Europe and globally experience more negative impacts than the UK (comparatively). However, it is highlighted these studies may not capture all risks due to their aggregated nature, they do not consider other constraints (e.g. over land or water), and they may be over optimistic on market adaptation and the potential for trade (and how this may change with Brexit and other factors).

What is missing?

The evidence base has generally increased since CCRA1 in terms of economic information. However, for 14 of the 61 risks and opportunities, even an indicative score was still not possible. There remains little economic evidence for the natural environment theme, though primarily this is driven by lack of evidence on the physical impacts of climate change, i.e. valuation is not the limiting factor (or at least, not the only limiting factor), and on the dependencies of economic sectors on nature (beyond the provisioning services). Many of the international risks are difficult to approach conceptually, and there is also less economic evidence.

There is also a particular gap identified around Net Zero. These commitments will change the receptors that climate change will act upon (e.g. the energy system), altering risks positively or negatively. At the same time, climate change could make the net zero target harder (or easier) to achieve, e.g. by increasing over-heating risk in summer or reducing energy demand in winter. Further work is needed to consider how the CCRA3 risks could change under a Net Zero future. This is particularly important to encourage synergistic mitigation-adaptation policies.

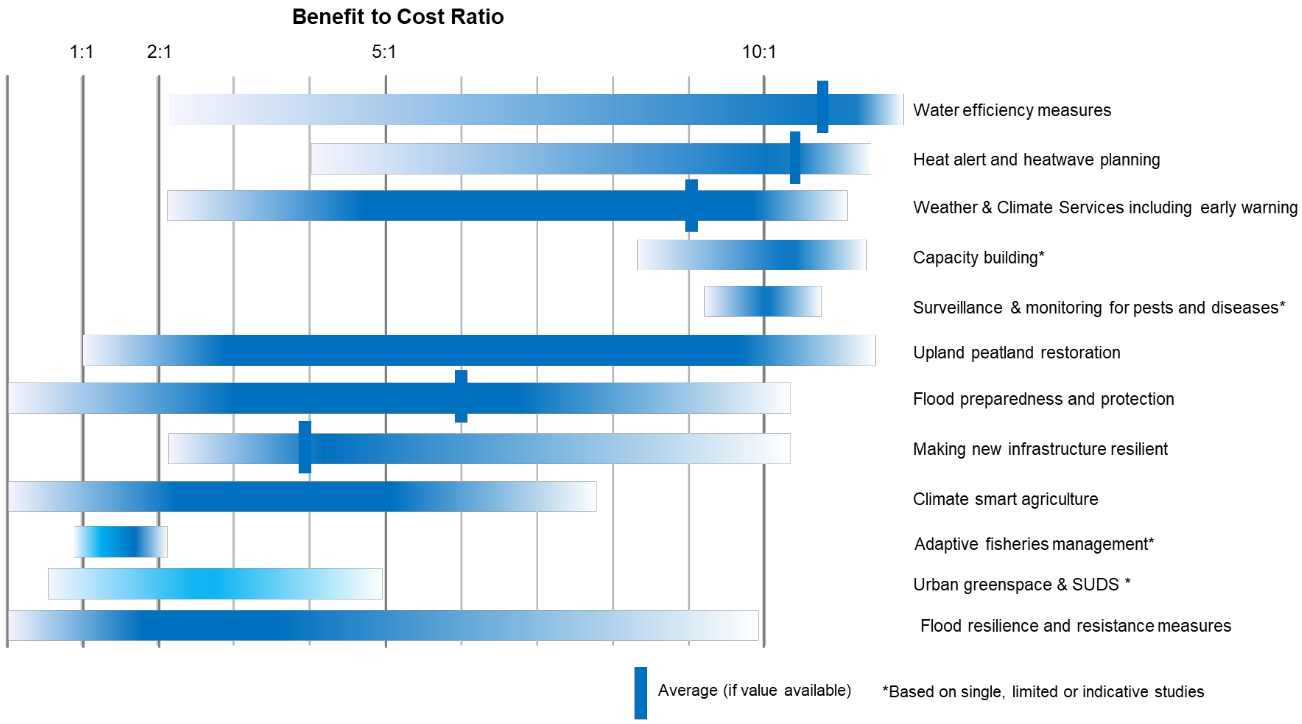
One other area that has been poorly captured in the valuation evidence base is around low probability-high impact events. This includes the so-called climate tipping points, but also high warming scenarios or extreme sea-level rise (including high++ scenarios). There is some limited evidence that indicates that these events could have extremely large economic costs, plausibly even non-marginal, though they would not only affect the UK. These outcomes are critical in the consideration of mitigation policy, because they go beyond the limits of adaptation. Furthermore, a new literature has emerged since CCRA1 on potential socio-economic tipping points (Van Ginkel, 2020dcxxx), which either arise as a cascading impact from a climate tipping point, or arise from a tipping point further down the impact chain. Again, these are a particular concern for high warming scenarios and they could lead to very large economic impacts (e.g. Tesselaar et al, 2020dcxxxi).

What are the benefits of adaptation?

The monetary valuation study in CCRA3 also undertook an evidence review of the costs and benefits of further adaptation action for all individual risks and opportunities, as part of Task 3b of the CCRA3 Methodology. As this review was based on the available evidence, the findings are partial, and can only be considered indicative. Furthermore, it is stressed that there are a very large number of caveats in transferring the results of existing cost-benefit studies of adaptation. This is due to the high site- and context-specificity, but also because the long time periods and high levels of uncertainty make quantification of benefits and thus economic analysis challenging.

Nonetheless, the review found an increased body of evidence, particularly since previous CCRAs, and identified potentially high economic benefits from further adaptation for many of the CCRA3 risks and opportunities. The findings for a selection of individual risks are summarised in the figure below.

This identifies that many early adaptation investments deliver high value for money. The benefit-cost ratios typically range from 2:1 to 10:1 – i.e., every £1 invested in adaptation could result in £2 to £10 in net economic benefits. The analysis also found that adaptation also often leads to important co-benefits, so as well as reducing potential losses from climate change, it often generates direct economic gains, or leads to social or environmental benefits. There are benefits from taking further adaptation action for almost every risk assessed in the CCRA report.



Notes: Figure shows the indicative benefit:cost ratios and ranges for a number of adaptation measures. It is based on the evidence review undertaken in the CCRA3 Valuation study, which was co-funded by the EU's Horizon 2020 RTD COACCH project (CO-designing the Assessment of Climate CHange costs). Vertical bars show where an average BCR is available, either from multiple studies or reviews. It is stressed that BCRs of adaptation measures are highly site- and context-specific and there is future uncertainty about the scale of climate change: actual BCRs will depend on these factors.

The supporting information for this figure is included in the box.

Water efficiency measures. There are studies which consider demand-side measures that can be introduced by homes, many of which are no-regret and low-regret. The study by Arup (2008[dcxxxii]) looked at a range of water saving measures, and estimated costs and pay-back times. A similar study was commissioned by the CCC (Davis Langdon, 2011[dcxxxiii]) looking at cost-effectiveness of alternative household options, and this was updated by Wood Plc (2019[dcxxxiv]) updating a previous cost-curve study. These studies identify estimated measures with benefit to cost ratios above 1 for different house types, comparing new build vs. discretionary retrofit. There has also been research by the EST (2019[dcxxxv]) on the costs and benefits of water labelling options, which finds very high benefit to cost ratios.

Heat alert and heatwave planning. There is some ex ante and ex post evidence on the benefits of heat alert systems for reducing urban heat fatalities internationally which indicates very high BCRs (e.g. Ebi et al., 2004[dcxxxvi]; Toloo et al, 2013[dcxxxvii]). There is currently no published data on the costs and benefits of the Heatwave Plan and HHWS in England, although an evaluation led by PHE is expected to be published soon. However, there has been economic analysis of the potential BCRs of other HHWS, and how these will change with climate change, that takes account of rising benefits but also rising resource costs. Hunt et al., (2016dcxxxviii) estimated a baseline BCR of 11:1 from the HHWS for London currently, and found that this increased under climate change (depending on the scenario, to between 21:1 to 28:1). Similar BCRs are also reported for heat alert warning in studies across Europe (UBA, 2012[dcxxxix]; Bouwer et al., 2018[dcxl]; Chiabai et al., 2018[dcxli]). The values are site- and context-specific, but BCRs also depend critically on the valuation of avoided fatalities, and whether this uses a Value of Statistical Life, (VSL), or some form of adjustment (e.g. Value of Life Year Lost or Quality Adjusted Life Years) – use of VSL considerably increase the BCRs. There are other related measures that extend HHWS to target health related mortality as part of heatwave plans, that include supporting interventions in the health and social care sectors: initial reviews of these find they also offer potentially high benefit to cost ratios (Pohl et al., 2014[dcxlii]; Watkiss et al., 2019[dcxliii]) there

Flood preparedness and protection. There are numerous studies of flood preparedness and prevention measures in reducing current flood impacts, and future flood impacts from climate change. One of the more comprehensive reviews of current BCRs is ECONADAPT (2015)[dcxliv]. This study compiled a database of DRM investments for floods in Europe containing 110 observations on investments/projects from 32 studies and databases, covering 16 European countries, and including ex ante and ex post studies. This found that investments in flood risk protection in Europe had, on average, a Benefit-to-Cost Ratio (BCR) of 5.9, whilst the median BCR was 3.0. DRM investments that enhanced preparedness to disasters had the highest economic returns, while investment that mitigate the damage of floods following the event also show high BCRs. Preparedness had the highest mean BCR (10.8), followed by ex post flood damage mitigation (BCR = 8.5), "hard" flood control such as dikes (4.1). These BCR findings are supported by other reviews: a systematic review (Mechler, 2016[dcxlv]) of flood risk management appraisal (both ex ante and ex post) found average BCRs of 5 for flood related risks. In all cases, BCR results are very- site- and context specific and vary further, depending on whether intangible as well as tangible benefits are included, and whether indirect effects are included. They also depend on the objectives used for setting flood protection levels, i.e. whether based on the economic optimal level or to meet acceptable risk levels (i.e. defined return levels for standards of protection). When considering future climate change, a number of studies show that BCRs are similar or larger than those for the present day (e.g. Brown et al., 2011[dcxlvi]; Rojas et al., 2013[dcxlvii]; Lincke et al. 2018[dcxlviii]; Ward et al. 2017[dcxlix]). However, it should be noted that these studies often apply highly stylised modelling rather than real policy investments, and/or decision making under uncertainty. In the UK, flood investments have to pass a CBA threshold, and therefore by definition have high benefit to cost ratios. The analysis of the long-term investment strategy (EA, 2019[dcl]) reports that the overall ratio is about 5:1 in England and Wales.

Weather and Climate Services including Early Warning Systems (EWS). This includes a range of services that incorporate weather forecasts (e.g. up to 10 days), climate services (e.g. seasonal forecasts), and early warning systems for extreme weather. For weather and climate services, reviews find high benefit to cost ratios, across a range of sectors (agriculture, energy, transport, water), e.g. Clements et al. (2013) surveyed 139 studies[dcli] and WMO (2015[dclii]) reviewed economic benefits. ECONADAPT (2017[dcliii]) undertook a review and found BCRs from 2:1 up to 36:1. Economic benefits arise from the use of services to improve decisions (sometimes known as the value of information). Values vary with site and location, and benefits depend critically on the delivery of climate information along the value chain (forecast accuracy, communication and reach, uptake and use, effectiveness). There are several reviews of the BCRs of early warning systems (e.g. Shreve and Kelman, 2014[dcliv]) and most recently, the Global Commission on Adaptation (2019[dclv]), reported an average BCR for EWS of 9:1, with a range of 3 – 16:1, though this was based on indicative, global analysis (not a detailed review of individual studies). Values vary with site and location, and especially on whether intangibles are valued (notably reduced loss of life). Note that while BCRs can increase under future climate change, costs of EWS and actions taken, and residual damage, also increase, due to increased frequency of extreme events.

Capacity building. Capacity building is generally reported as being extremely effective, but is very challenging for valuation. There have been some international reviews that identify high economic benefits (LSE, 2016)[dclvi] as well as a number of context-specific studies that have estimated BCRs, reporting results of >10:1 though these are limited in transferability to the specific UK context[dclvii],[dclviii].

Making new infrastructure climate resilient. Infrastructure often has a long life-time, and new infrastructure built over the next few years may operate under a very different climate to today. If these future risks are not considered, climate change will cause asset damage or failure, and affect operating costs and/or revenues. There is an opportunity to design infrastructure to be climate resilient when it is built. Recent analysis by the World Bank has identified that on average, building climate resilience into new infrastructure involves low marginal cost, and has a benefit to cost ratio of 4:1 (Hallegette et al., 2019[dclix]). This analysis was further refined in the Global Commission on Adaptation (2019[dclx]) report, which also reports BCRs of 4:1 (with a range of 2:1 to 10:1). However, both these studies are highly aggregated and stylised, and they are not based on specific ex ante or ex post review of projects. Actual analysis of the costs and benefits of making specific infrastructure climate-resilient shows these are extremely site- and context-specific (e.g. ADB, 2014[dclxi]; ADB, 2021[dclxii]), and BCRs vary with the objectives set for adaptation as well as the adaptation options considered. They also vary with climate change and scenario projections, how uncertainty is included (with decision making under uncertainty), as well as discount rates. There is therefore a very large range of potential BCRs, including the potential for economic maladaptation (BCRs <1).

Peatland restoration. There are some economic studies of peatland restoration in the UK. These are complex to undertake, because comparison of the costs and benefits are characterised by upfront restoration costs and future benefit streams which are uncertain; time periods and discount rates used are therefore key assumptions. Furthermore, analysis requires quantification and valuation of ecosystem services (both for baseline and future climate scenarios, and with adaptation): this involves considerable challenges as well as uncertainty. The net benefits of restoration clearly increase if more ecosystem services are included, the longer the time-period considered, and the greater the assumed pace and extent of climate change (though importantly, climate change strengthens the case for restoration). There are reported cost-benefit ratios (Harlow et al., 2012[dclxiii]; Moxey and Moran, 2014[dclxiv]; Bright, 2017[dclxv]; CCC, 2013) for different sites, and Watkiss et al., (2019[dclxvi]) report that these BCRs range between 1.3:1 and 12:1, depending on the time-horizons and benefits considered.

Climate smart agriculture (CSA). Climate smart agriculture aims to deliver on triple outcomes: productivity (income growth), mitigation and adaptation. Actual delivery against the three areas varies by practice and context, and values are extremely site and context specific. Internationally, there is a body of evidence on the benefit to cost ratios of CSA, which find positive ratios. For example, ex ante analysis of 32 country-level projects (Ferrarase et al 2016[dclxvii]) estimated a BCR of 2:1 on average, but with a range from 1:1 to 7:1. Values are highly site-specific, reflected in large BCRs differences for similar interventions in different places, whilst benefits depend on whether non-market benefits are included, as well as whether opportunity costs, transaction costs and implementation costs are included[dclxviii]. There are also questions of the transferability of these findings to the UK context. In the UK, CSA options analysed by SRUC (2013[dclxix]) found that with one exception - cover crops – agricultural interventions generated positive NPVs, although these were modest and there would still be challenges to encourage farmers to adopt them. Posthumus et al. (2015[dclxx]) assessed soil erosion measures. The study concluded that that only a few erosion control measures had a positive financial NPV. It identified tramline management, high-density planting, mulching, buffer strips and sediment traps as the measures with the potential for promotion and adoption in the UK, as these have the highest economic cost-effectiveness. In all cases, there was a very wide range in reported BCRs for these interventions

Monitoring and surveillance of pests and diseases. There is evidence in the CCRA3 valuation study on the costs of pests and disease outbreaks, and the costs and benefits of managing these risks. This indicates that once these outbreaks become established, managing pests and disease is less cost-effective. The adaptation literature reports that there is a strong case for enhanced monitoring and surveillance as well as early response, and analysis in the UK (SRUC, 2013[dclxxi]) suggests this would be highly beneficial, with a benefit to cost ratio of up to 10:1.

Fisheries management. There is some international literature, including reviews, on the economics of adaptation in the fisheries sector[dclxxii], as well as some UK analysis on potential economic costs of climate change (e.g. Fernandes et al. (2017[dclxxiii]) and the costs and benefits of adaptation (Frontier et al,. 2013[dclxxiv]). Watkiss et al (2019[dclxxv]) undertook initial analysis to look at the benefits of moving to an adaptive management approach in the fisheries sector, based on the scale-up of current research and monitoring activities (based on Costello et al. 2009[dclxxvi]). This analysis indicated there could be an increase in fishery value (through the value of information) with a positive benefit to cost ratio. The study also looked at the potential benefits of increasing marine protected areas (or protection levels within them) as a form of adaptation and found them likely to significantly outweigh costs.

Green infrastructure (urban green space and sustainable drainage). Watkiss et al. (2019[dclxxvii]) reviewed the literature on the costs and benefits of urban green infrastructure. This highlighted that the role of green infrastructure as an adaptation option requires an analysis of its' relative attractiveness compared to other options, and that effectiveness is highly site, context and location specific. Measures can have positive BCRs provided that all benefits are valued, including non-market ecosystem service benefits (especially recreational benefits). There are some benefit to cost ratios of green flood resilience, notably sustainable drainage systems in the literature. Ossa-Moreno et al. 2017[dclxxviii] assessed five SuDS schemes, with BCRs ranging between 0.9:1 and 1.8:1. It is noted there are also some economic studies of larger nature-based solutions for flood management, for schemes across Europe[dclxxix], and in the UK (EA, 2009[dclxxx]; Frontier et al., 2013[dclxxxi]). These show that these schemes can have positive benefit to cost ratios, especially when all ecosystem services are included, but they also vary according to time periods and discount rates considered. There are also studies that report high BCRs for schemes that combine grey and green schemes[dclxxxii], reflecting the fact that NBS may be more appropriate for mitigating more frequent, low level flooding, rather than major extremes. In terms of urban cooling potential, analysis of the costs and benefits of green space as an adaptation option (Mendizabal and Peña, 2016[dclxxxiii], Loibl et al, 2015[dclxxxiv]) does show positive BCRs for small urban schemes, driven by the overall ecosystem services benefits (not just cooling). However, these studies often find that large, new green space has low benefit to cost ratios for cooling, due to the high opportunity costs associated with land-use (and land-use values) in major urban centres. Smaller schemes can address some of the cost barriers, but have much lower / or more localised effects. The review found very mixed results for green roofs with low or sometimes negative benefit to cost ratios.

Property resilience and resistance. There has been a series of economic studies on property resilience and resistance measures in the UK. These include EA (2015[dclxxxv]), Royal Haskoning DHV (2012[dclxxxvi]) and Wood Plc

(2019[dclxxxvii]). In general, this literature reports that measures are more expensive if retrofitted rather than installed in new builds. The Wood study, as the most recent, reports that a number of flood resilience and resistance measures do have benefit to cost ratios of greater than one. They report that flood resistance packages across all types of residential dwellings have BCRs>1 where there is a greater than 1% chance of Annual Exceedance Probability (AEP). Flood resilience measures were largely shown to have positive BCRs in newbuild dwellings for the same criteria, and the study provides a list of the flood resilience measures that had a BCR>1. However, these findings are very site and context specific, not least because they depend on flood probabilities, and type of flooding (recurrence and depth), all of which alter the benefit to cost ratios.

This highlights that there are benefits to acting early. Furthermore, delaying adaptation will make it much harder to tackle future climate risks and may make large future costs inevitable: opportunities for building resilience will decline with time (GCA, 2019[dclxxxviii]).

At the same time, some decisions and actions can be delayed: a key issue is therefore to identify where what is urgent to do now, and what can be done later as part of an iterative, adaptive management approach. There are three areas where early action is needed and can be justified in economic terms (Watkiss and Betts, 2021[dclxxxix]).

First, as highlighted above, the UK already experiences large economic costs from climate extremes today, and these are growing. There are therefore large net economic benefits today from reducing these with low- and no-regret actions, which have high benefit to cost ratios (OECD, 2015[dcxc]).

Second, in some areas there is a large economic cost from delaying action. This involves decisions or investment that could lead to very large future economic costs, that will be costly to address or are irreversible. There is a one-off opportunity to avoid these risks now, but if this is not taken, we commit (lock-in) to large future impacts. A good example is infrastructure. Infrastructure built over the next five years will operate under a very different climate to today. If these future risks are not considered, climate change will cause asset damage or failure, and affect operating costs and/or revenues. There is a one-off opportunity to design infrastructure to be climate resilient when it is built, and this has a benefit to cost ratio of 4:1 (Hallegette et al., 2019[dcxci]). A further example is with the hundreds of thousands of new homes being built each year in the UK, which are currently not designed for future overheating risks. Similar issues arise with land-use, as this locks-in development patterns for decades.

Finally, there are some extremely low-cost preparatory actions that can be taken to improve future decisions, effectively providing option values[dcxcii]. This involves developing adaptive management plans, especially for decisions that have long lead times or involve major future change in the future that is uncertain.

What has been difficult and what are recommendations for future analysis?

The valuation exercise in CCRA3 has been much more challenging than in CCRA1, because of the use of a synthesis approach in the underlying CCRA Technical Report. It has required more work to go back to the primary physical impact literature, and it has relied more on the use of existing economic studies in a synthesis analysis. In turn, this has made the reporting and direct comparison of monetary values for individual risks and opportunities problematic, because primary studies use different scenarios, socio-economic assumptions, etc. This means the valuation results here are 'messier' than for CCRA1.

Looking forward, it is notable that by the time of CCRA4, it will have been fifteen years since a systematic, comprehensive and consistent analysis of risks and opportunities for the UK has been conducted, including an economic assessment. Given the scale of economic cost being projected in CCRA3, and the need to inform future risk management and adaptation decisions, it is important to plan how CCRA4 can incorporate a more advanced analysis (including economic analysis).

Finally, alongside any analysis of risks and opportunities, there is a need to improve the economic analysis of how current (and planned) adaptation is reducing these future risks (or enhancing opportunities). There is very little information – from either government policy studies or the academic literature – on the real-world impact of current adaptation. This is partly because there is insufficient ex post data, and partly because ex ante studies are very difficult. However, it is a major gap and would have significant benefits for the economic analysis in CCRA4.

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